

Proteomics analysis of human endothelial cells after short-term exposure to mobile phone radiation

Reetta Nylund

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STUK – Radiation and Nuclear Safety Authority
Aalto University School of Science

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Proteomics analysis of human endothelial cells after short-term exposure to mobile phone radiation

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Abstract

Mobile phones have been a part of our everyday life in the developed world since the late 1990s. This has raised concerns over the potential health risks of mobile phone use. Biological and health effects potentially caused by mobile phone radiation have been extensively studied and several biological and medical endpoints have been examined. So far, results have not been conclusive on the potential effects of mobile phone radiation.

Mobile phones generate a modulated radio frequency electromagnetic field (RF-EMF), which is a form of non-ionizing radiation. This means that mobile phone radiation does not have enough energy to ionize atoms and it cannot break chemical bonds directly (e.g., in DNA strands). There could, however, be other mechanisms by which mobile phone radiation may affect cellular and physiological functions. Whether these mechanisms exist is unknown.

In this thesis, large-scale screening techniques, such as proteomics, were applied to examine changes on the proteome level after exposure to mobile phone radiation. Proteomics techniques allow the screening of several hundreds, and even thousands, of proteins simultaneously, and are thus more efficient than single endpoint techniques.

Four different types of human endothelial cells (two cell lines, two types of primary cells) were exposed to two types of mobile phone radiation (900 and 1800 MHz GSM). The proteome of these cells was examined immediately after short-term exposure using two-dimensional gel electrophoresis (2DE). Two protein detection/analysis techniques were used: silver staining for the cell line samples and difference gel electrophoresis (DIGE) for the primary cells. 2DE-DIGE technology is currently a state-of-the-art technique in 2DE studies.

Several changes were found in the proteome of the human endothelial cell line EA.hy926 after exposure to 900 MHz GSM mobile phone radiation. In addition, the proteome of a variant of the same cell line, the EA.hy926v1, was affected after 900 MHz GSM mobile phone radiation exposure, but the altered proteins were different from those in the EA.hy926 cells. The changes in the

proteome of the EA.hy926 cells were weaker after 1800 MHz GSM exposure compared to those after 900 MHz GSM exposure. Furthermore, certain proteins affected earlier after 900 MHz GSM exposure were unaffected after 1800 MHz GSM exposure.

The proteome of the primary human endothelial cells was not affected after 1800 MHz GSM exposure when examined using 2DE-DIGE technology. 2DE-DIGE technology is more reliable than the technology used with the EA.hy926 cell line, and these results should therefore be highly relevant when assessing the potential immediate effects of mobile phone radiation.

The results presented in this thesis on the proteome-level effects of mobile phone radiation exposure are contradictory. The results with EA.hy926 cells suggest that minor effects do occur, whereas no effects were observed when using the more reliable 2DE-DIGE technology and primary cells. The responses with EA.hy926 cells varied according to the cell variant and exposure conditions, and consistent responses at the cellular level could not therefore be identified. Further research is recommended to understand the variation in responses and whether consistent cellular-level responses exist.

NYLUND Reetta. Ihmisen endoteelisolujen proteomiikka-analyysi lyhytaikaisen matkapuhelinsäteilyaltistuksen jälkeen. STUK-A250. Helsinki 2011, 100 s. + liitteet 73 s.

Avainsanat: Radiotaajuiset sähkömagneettiset kentät, matkapuhelinsäteily, ihmisen endoteelisolut, proteomiikka, kaksisuuntainen geelielektroforeesi, proteiinien ilmentyminen

Tiivistelmä

Matkapuhelimet ovat olleet osa jokapäiväistä elämäämme 1990-luvun loppupuolelta lähtien, mikä on aiheuttanut huolta niiden mahdollista terveysvaikutuksista. Matkapuhelinsäteilyn mahdollisia biologisia ja terveysvaikutuksia on tutkittu laajalti ja tarkasteltavana on ollut useita erilaisia biologisia ja lääketieteellisiä ilmiöitä. Toistaiseksi tutkimustulosten perusteella ei ole saatu varmuutta, onko matkapuhelinsäteilyllä mahdollisia vaikutuksia.

Matkapuhelimet lähettävät radiotaajuisia aaltoja, jotka ovat ionisoimatonta säteilyä. Matkapuhelinsäteilyn energia ei riitä atomien ionisoimiseen ja se ei pysty suoraan rikkomaan kemiallisia sidoksia (esimerkiksi DNA-ketjussa). Matkapuhelinsäteily saattaa kuitenkin vaikuttaa solutason fysiologisiin toimintoihin muiden mekanismien välityksellä. Tällaisten mekanismien olemassa olosta ei ole toistaiseksi saatu varmuutta.

Tässä väitöskirjassa sovellettiin laaja-alaisia seulontatekniikoita, kuten proteomiikkaa, proteiinitason muutosten tutkimiseen matkapuhelinsäteilyaltistuksen jälkeen. Proteomiikka-menetelmien avulla voidaan yhtäaikaaisesti tutkia satoja tai jopa tuhansia proteiineja ja ne ovat näin ollen tehokkaampia kuin yksittäistä ilmiötä tutkivat menetelmät.

Tutkimuksessa käytettiin solumallina ihmisen endoteelisoluja. Solumalleja oli yhteensä neljä (kaksi solulinjaa ja kahdenlaisia primäärisoluja) ja niitä altistettiin kahdella eri taajuudella (900 ja 1800 MHz GSM). Muutoksia solujen proteomissa tutkittiin välittömästi lyhytkestoisen altistuksen jälkeen kaksisuuntaista geelielektroforeesia (2DE) käyttäen. Tutkimuksissa käytettiin kahta erilaista proteiinien värjäys-/analysointitekniikkaa: solulinjanäytteille hopeavärjäystä ja primäärisoluille fluoresoivia leimoja (DIGE-tekniikka). 2DE-DIGE-tekniikka edustaa parasta mahdollista teknologiaa 2DE-tutkimuksissa.

Tutkimuksissa löydettiin useita muutoksia ihmisen endoteelisolulinjan EA.hy926:n proteomissa 900 MHz GSM -altistuksen jälkeen. Lisäksi muutoksia

havaittiin saman endoteelisolulinjan muunnoksen, EA.hy926v1:n, proteomissa 900 MHz GSM -altistuksen jälkeen, mutta nämä muutokset olivat erilaisia kuin EA.hy926-soluissa. EA.hy926-solujen proteomissa löydettiin muutoksia myös 1800 MHz GSM -altistuksen jälkeen, mutta nämä muutokset olivat heikompia kuin 900 MHz GSM -altistuksen jälkeen. Lisäksi tiettyjen proteiinien ilmentyminen, joka muuttui aiemmin 900 MHz GSM -altistuksen jälkeen, ei muuttunut 1800 MHz GSM -altistuksen jälkeen.

Primäärysten ihmisen endoteelisolujen proteomissa ei havaittu muutoksia 1800 MHz GSM -altistuksen jälkeen, kun tutkimuksissa käytettiin 2DE-DIGE-tekniikkaa. 2DE-DIGE-tekniikka on luotettavampi kuin menetelmä, jota käytettiin EA.hy926-solujen tutkimiseen. Näin ollen näillä tuloksilla tulisi olla paljon painoarvoa arvioitaessa lyhytkestoisen matkapuhelinsäteilyaltistuksen mahdollisia välittömiä biologisia vaikutuksia.

Tässä väitöskirjassa esitetyt tulokset matkapuhelinsäteilyn vaikutuksista solujen proteomin tasolla ovat ristiriitaisia. EA.hy926-soluilla saadut tulokset näyttävät, että joitakin muutoksia voi esiintyä altistuksen jälkeen. Luotettavammalla 2DE-DIGE-tekniikalla ja primäärisoluilla ei puolestaan havaittu muutoksia altistuksen jälkeen. Vaikutukset EA.hy926-soluissa vaihtelivat solumuunnoksen ja altistusolosuhteiden perusteella ja näin ollen ei ole mahdollista havaita yhdenmukaista solutason vastetta matkapuhelinsäteilylle. Jatkotutkimuksilla tulisi selvittää, miksi vaikutukset vaihtelevat ja onko yhdenmukaista solutason vastetta olemassa.

Contents

Abstract	5
Tiivistelmä	7
Contents	9
Original Publications	12
Author's Contribution	13
List of Abbreviations	14
1 Introduction	16
2 Review of the Literature	18
2.1. Biological and health effects of mobile phone radiation	18
2.1.1. Mobile phone radiation	18
2.1.2. Potential mechanism	19
2.1.3. Overview of potential effects	20
2.1.3.1. Research approaches	20
2.1.3.2. Cancer-related studies	21
2.1.3.3. Human volunteer studies	22
2.1.3.4. Physiological endpoints in animal studies	24
2.1.3.5. Genotoxicity	25
2.1.3.6. Cellular effects	27
2.1.4. Protein and gene expression	29
2.1.4.1. Heat shock proteins	29
2.1.4.2. Proto-oncogenes	32
2.1.4.3. Signal transduction pathways and structural proteins	34
2.1.4.4. Transcriptome	36
2.1.5. Conclusions based on the review of the literature	39
2.2. Proteomics	40
2.2.1. Overview	40
2.2.2. Two-dimensional gel electrophoresis	42
2.2.2.1. Principles	42
2.2.2.2. Challenges and recent developments	43
2.2.3. Proteomics in mobile phone radiation studies	46

3	Aims of the Present Study	52
4	Materials and Methods	53
4.1.	Cell cultures	53
4.1.1.	Human endothelial cell line	53
4.1.2.	Primary human umbilical vein endothelial cells	54
4.1.3.	Primary human brain microvascular endothelial cells	55
4.2.	Mobile phone radiation exposures	55
4.2.1.	GSM 900 MHz exposure set-up	55
4.2.2.	GSM 1800 MHz exposure set-up	56
4.3.	Two-dimensional gel electrophoresis	57
4.3.1.	Sample preparation	57
4.3.2.	Sample labeling	57
4.3.3.	Isoelectric focusing	58
4.3.4.	SDS-PAGE	58
4.3.5.	Gel staining and image acquisition	58
4.3.6.	Data analysis	59
4.3.6.1.	PDQuest software	59
4.3.6.2.	DeCyder software	59
4.4.	Mass spectrometry	60
4.4.1.	In-gel digestions	60
4.4.2.	MS data analysis	60
4.5.	Western blotting	60
4.6.	Immunocytochemistry	61
5	Results	62
5.1.	Effects on the proteome after 900 MHz GSM exposures (I–III)	62
5.1.1.	Human endothelial cell line EA.hy926	62
5.1.2.	Human endothelial cell line EA.hy926v1	63
5.2.	Effects on the proteome after 1800 MHz GSM exposures (IV, V)	63
5.2.1.	Human endothelial cell line EA.hy926	64
5.2.2.	Primary human endothelial cells	65
6	Discussion	66
6.1.	Effects on the proteome after mobile phone radiation exposure	66
6.2.	General remarks on proteomics results in the light of technological development	70
6.3.	Future aspects	71

7	Conclusions	73
	Acknowledgements	74
	References	76
	Appendix 1	101

Original Publications

- I Leszczynski D., Nylund R., Joenväärä S., and Reivinen J.:
Applicability of discovery science approach to determine biological effects of mobile phone radiation
Proteomics 2004, 4: 426–431

- II Nylund R. and Leszczynski D.:
Proteomics analysis of human endothelial cell line EA.hy926 after exposure to GSM 900 radiation
Proteomics 2004, 4: 1359–1365

- III Nylund R. and Leszczynski D.:
Mobile phone radiation causes changes in gene and protein expression in human endothelial cell lines and the response seems to be genome- and proteome-dependent
Proteomics 2006, 6: 4769–4780

- IV Nylund R., Tammio H., Kuster N., and Leszczynski D.:
Proteomic analysis of the response of human endothelial cell line EA.hy926 to 1800 GSM mobile phone radiation
J Proteomics Bioinform 2009, 2: 455–462

- V Nylund R., Kuster N., and Leszczynski D.:
Analysis of proteome response to the mobile phone radiation in two types of human primary endothelial cells
Proteome Science 2010, 8:52 (pages 1–7)

Additionally, some unpublished data are discussed.

Author's Contribution

- I Dariusz Leszczynski had the main responsibility for the designing and preparing this publication. The author (RN) participated in the design and provided data for the manuscript.
- II, IV, V RN had the main responsibility for the execution of this study: the development of the experimental platform, performing of the experiments, and data analysis. The study was designed and the manuscript prepared in co-operation with Dariusz Leszczynski.
- III RN had the main responsibility for the proteomics experiments presented in this study: the execution of the experiments and data analysis. The study was designed and the manuscript prepared in co-operation with Dariusz Leszczynski.

The author has the main responsibility for the unpublished data discussed here: the execution of the experiments and data analysis. The studies were designed in co-operation with Dariusz Leszczynski.

List of Abbreviations

2DE	Two-dimensional gel electrophoresis
ACN	Acetonitrile
ACTH	Adrenocorticotrophic hormone
BBB	Blood-brain barrier
BSA	Bovine serum albumin
BVA	Biological variation analysis module in DeCyder analysis software
CDMA	Code division multiple access
CHAPS	3-[(3-Cholamidopropyl)dimethylammonio]-1-propanesulfonate
CW	Continuous wave
ddH ₂ O	Double distilled water
DIGE	Difference gel electrophoresis
DTT	Dithioreitol
EA.hy926	Human endothelial cell line
ECL	Enhanced chemiluminescence
EDA	Extended data analysis module in DeCyder analysis software
EDTA	Ethylene diamine tetraacetic acid
EEG	Electroencephalography
EMF	Electromagnetic field
FDR	False discovery rate
FDTD	Finite-difference time domain
GSM	Global system for mobile communications
HBMEC	Human brain microvascular endothelial cell
HSC	Heat shock cognate
HSP	Heat shock protein
HUVEC	Human umbilical vein endothelial cell
IAA	Iodoacetamide
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
IEF	Isoelectric focusing
IPG	Immobilized pH gradient
LR	Linear reflectron
LTE	Long-term evolution
MALDI-TOF	Matrix-assisted laser desorption/ionization time of flight
MS	Mass spectrometry/ mass spectrometer
MW	Molecular weight
NEPHGE	Non-equilibrium pH gradient electrophoresis
NH ₄ HCO ₃	Ammonium bicarbonate

NMT	Nordic mobile telephone
ODC	Ornithine decarboxylase
PAGE	Polyacrylamide gel electrophoresis
PBS	Phosphate buffered saline
PCA	Principal component analysis
PCR	Polymerase chain reaction
pI	Isoelectric point
PMF	Peptide mass fingerprint
PMSF	Phenylmethanesulphonyl fluoride
PVDF	Polyvinylidene fluoride
PW	Pulsed wave
RF	Radio frequency
ROS	Reactive oxygen species
RT	Real time
SAGE	Serial analysis of gene expression
SAR	Specific absorption rate
SDS	Sodium dodecyl sulphate
Tris-HCl	Tris(hydroxymethyl)aminomethane hydrochloride
UMTS	Universal mobile telecommunications system
WB	Western blot/blotting
WCDMA	Wideband code division multiple access
WHO	World Health Organization

1. Introduction

Mobile phones have been a part of everyday life for most people in the developed world since the late 1990s. At the end of 2007 there were over six million mobile phone subscriber connections in Finland, corresponding to 115 subscriber connections per 100 inhabitants (Tilastokeskus 2008). Worldwide, the number of mobile phone subscribers has been estimated to have reached five billion (International Telecommunication Union (ITU) 2011). Simultaneously with the increase in the use of mobile phones, concern over the potential health risks due to mobile phone radiation has also arisen. Mobile phone technology has improved substantially since the first generation of cell phones, but the way they are used has also changed over time and is still changing. At first, mobile phone calls were expensive and the use of mobile phones was rare. However, mobile phones have developed and nowadays they serve people more as entertainment centers that are used for listening to music, photographing, surfing the Internet, and other purposes. In addition, land-line networks are no longer maintained in certain areas, causing phone calls to be transferred to wireless networks in these areas, thus further increasing the use of mobile phones.

Studies on the potential health and biological effects of mobile phone radiation have been extensively conducted over the years. Epidemiological as well as *in vivo* and *in vitro* approaches have been applied to examine the potential health and biological effects of mobile phone radiation. A few large epidemiological studies have been performed, mainly related to the incidence of cancer due to mobile phone use. Furthermore, human studies have been carried out to examine the effects of mobile phone radiation on sleep, different cognitive functions and behavioral aspects. There have also been several studies related to cancer incidence, genotoxic effects, cellular behavior and gene and protein expression *in vivo* and *in vitro*. So far, a number of these studies have focused on a single medical/biological endpoint (e.g., cancer incidence, apoptosis, or single protein expression). However, the results of the various studies have been contradictory. There is currently no consensus on whether mobile phones might have health or even biological effects, and in particular, no plausible mechanism for the effects of mobile phone radiation has been suggested.

Mobile phones generate a modulated radio frequency electromagnetic field (RF-EMF), which is a form of non-ionizing radiation. Mobile phone radiation is unable to cause ionizations in atoms or molecules and it does not have enough energy to directly break chemical bonds (e.g., in DNA strands). However, it is unknown whether mobile phone radiation could affect cellular and physiological functions by other mechanisms. A few hypotheses of these mechanisms have been presented, but to date there has been no generally accepted mechanism for

the potential non-thermal effects of mobile phone radiation.

Since the mid-1990s, new genome-wide screening techniques ('omics-techniques') have greatly developed and have become increasingly popular in research. These large-scale screening techniques allow the simultaneous examination of several endpoints, e.g., at the gene (transcriptomics) or protein (proteomics) expression level. These techniques have been successfully applied in several research fields, from clinical biomarker discovery to various systems biology approaches.

In this thesis, non-thermal biological and health effects related to mobile phone-based radiation are discussed, with a special focus on protein expression *in vitro*. An application of large-scale screening techniques in mobile phone radiation research is presented, and proteomics methods were used in the presented research to investigate the effects of the mobile phone radiation. Human endothelial cells were used as an *in vitro* model and the cellular proteome was examined immediately after short-term exposure to mobile phone radiation.

2. Review of the Literature

2.1. Biological and health effects of mobile phone radiation

2.1.1. Mobile phone radiation

In everyday life, we are constantly surrounded by electromagnetic fields (EMF). There are natural sources of EMF, such as the earth's magnetic field, as well as man-made sources, such as power cables, domestic appliances, radio stations, mobile phones, wireless networks, and radars. Many technical systems, such as mobile phones, use modulated radio frequency electromagnetic fields (RF-EMF) to transfer information. Typically, RF-EMF refers to the frequency range from 100 kHz up to 300 GHz (Nyberg, Jokela 2006).

Currently, there are two public mobile phone systems in large-scale use in Finland: the second generation GSM (Global System for Mobile Communications) system operating at 900/1800 MHz and the third generation UMTS/WCDMA system (Universal Mobile Telecommunications System/Wideband Code Division Multiple Access) operating at around 2000 MHz. The first generation analogue NMT (Nordic Mobile Telephone, 450/900 MHz) system was shut down by the end of the last millennium. The fourth generation LTE (Long Term Evolution) network, operating at around 2600 MHz, was launched on a pilot scale in late 2010.

Mobile phones emit RF-EMF in specified frequency bands during the transmission phase (i.e., when speaking during a phone call). GSM phones emit a digital pulse-modulated signal. The maximum transmission power of GSM phones is 0.25 W at 900 MHz frequency and 0.125 W at 1800 MHz frequency. The maximum transmission power during one pulse, however, is 8-fold higher (i.e. 2 W at 900 MHz and 1 W at 1800 MHz), because the signal is emitted in pulses with a duration of 0.577 milliseconds in 4.615 millisecond frames (that is, the signal is only emitted during one eighth of the time). The signal in UMTS systems is more irregular than in GSM systems. In WCDMA systems, the signal is emitted on 5-Hz-wide radio channels. The maximum transmission power is 0.125 W and the peak transmission power below 1 W (Nyberg, Jokela 2006). Mobile phone systems continuously adapt the transmission power output level, and the maximum transmission power is only used when the field is weak, e.g., because of a long distance between the phone and the receiving base station.

The level of exposure to mobile phone radiation is generally measured as a specific absorption rate (SAR), which describes the power absorption per

unit mass and is expressed as W/kg. Basically, SAR represents the thermal load directed to the tissue from the electromagnetic field. A strong electric field might warm up tissues, and thermal effects of this kind are nowadays well understood (Adair, Black 2003). Based on these well-established biological effects of EMF, guidelines have been established to limit human exposure to RF-EMF. These guidelines have been published, for example, by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (International Commission for Non-Ionizing Radiation Protection (ICNIRP) 1998) and the Institute of Electrical and Electronics Engineers (IEEE) (The Institute of Electrical and Electronics Engineers (IEEE) 2006). In the EU area, RF-EMF exposure limits are based on the ICNIRP guidelines, and in Finland, for example human exposures are regulated by a decree of the Ministry of Social Affairs and Health (294/2002). These basic restrictions contain 10–100-fold safety margins, and for exposure of the general public SAR levels have been set to 0.08 W/kg concerning the whole body, 2 W/kg for local exposure to the head and torso, and 4 W/kg for local exposure to the limbs. The SAR levels for local exposures are calculated as an average in 10 g of tissue. Based on these basic restrictions, a maximum SAR of 2 W/kg is permitted for mobile phones. Mobile phones commonly operate close to the exposure limits, around SAR levels of 1 W/kg. Thus, mobile phones are the only RF sources that operate close to basic restriction limits. In addition, local exposures in certain small areas might exceed the basic restrictions. (International Commission for Non-Ionizing Radiation Protection (ICNIRP) 1998, Nyberg, Jokela 2006)

2.1.2. Potential mechanism

Electromagnetic fields induce an electric field and a current into the body. A strong electric field, depending on its frequency, might warm up tissues or disturb the neuronal functions. Thermal effects are based on energy absorption from the field to the tissue, which causes the oscillation of molecules. These types of effects are nowadays well known (Adair, Black 2003, Nyberg, Jokela 2006), and guidelines to limit human exposure to EMF are based on them. However, it is unclear whether RF-EMF might cause other non-thermal effects at low exposure levels.

Mobile phone radiation is non-ionizing, i.e. it is not able to cause ionizations in atoms or molecules. The minimum energy required for ionization of a ground state hydrogen atom is 13.6 eV, and the ionization energy for other atoms and molecules is also in the eV order of magnitude. The order of magnitude of the photon energy of RF-EMF, e.g., mobile phone radiation, is one millionth of the ionization energy and one thousandth of the thermal energy at room

temperature or the energy required to break weak non-covalent chemical bonds. Thus, the photon energy of mobile phone radiation is too weak to induce direct chemical changes and break chemical bonds directly (e.g., in DNA strands), and the mechanism for mobile phone radiation-based effects is therefore likely to be indirect, if such a mechanism exists at all. Several hypotheses for these potential mechanisms have been suggested (for a review, see e.g., Foster 2000, Nyberg, Jokela 2006, Sheppard, Swicord & Balzano 2008, Adair 2003), including for instance a reactive oxygen species (ROS)-mediated mechanism (Brocklehurst, McLauchlan 1996), oscillating resonances, and induced dipole moments. However, based on current knowledge, it seems that weak fields are quite unlikely to generate significant effects in their interactions (Adair 2003, Sheppard, Swicord & Balzano 2008). Thus, no generally accepted mechanism for the potential non-thermal mobile phone radiation-based effects has so far been established.

2.1.3. Overview of potential effects

2.1.3.1. Research approaches

Biological research regarding the potential biological and health effects of EMF has been conducted for decades and it has related to several different biological and health aspects. The studies have been conducted using different frequencies, exposure levels and durations as well as modulation types of RF-EMF. Several research strategies have been applied using epidemiology as well as *in vivo* and *in vitro* methods, since each of these approaches has its own strengths and weaknesses. Specifically, exposure assessment is one of the common challenges concerning all the study approaches in mobile phone radiation research.

Epidemiological studies aim to demonstrate a direct impact on humans and are thus usually considered to be the most suitable for human health risk assessment, which is an important issue in mobile phone radiation research. However, epidemiological studies in mobile phone radiation research are often limited by the assessment of exposure. In the studies executed so far, exposure assessment has often been carried out using questionnaires on mobile phone use completed by study participants. This might potentially cause bias in exposure assessment, e.g., due to recall bias. Human volunteer studies also provide direct evidence of the actual human response, but due to ethical reasons, these studies are limited to transient physiological phenomena. Studies *in vivo* can be used to mimic human studies to obtain physiological information in experimental situations where it is not possible to use human volunteers. Studies *in vitro* are extremely useful for determining basic biological effects and potential

mechanisms behind the effects, while they cannot be directly applied in health risk assessment.

In some of the early studies *in vivo* and *in vitro*, estimation of the exposure has been challenging, as the samples might have been heated to excess due to the RF-EMF exposure. Thus, it is unclear whether the effects potentially observed in these studies have been caused by heating or RF-EMF exposure (i.e., whether those are non-thermal effects). Furthermore, in certain studies the exposures have been executed by placing a regular mobile phone close to an animal cage or cell culture dishes. Such exposures do not allow reliable exposure assessment. Nowadays, specific exposure set-ups have been designed for studies both *in vivo* and *in vitro*. In the most optimized set-ups the study subjects are exposed to RF-EMF in a highly controlled environment and several factors such as temperature and field parameters can be monitored continuously during the exposure.

2.1.3.2. Cancer-related studies

One of the most common fears regarding mobile phone radiation exposure has been its potential ability to cause cancer. The cancer incidence due to mobile phone radiation exposure has been examined with epidemiological studies that examine the direct influence on humans. Additionally, effects on the incidence of cancer have been examined using animal studies.

Epidemiology provides the most direct evidence of the carcinogenic potential of specific agents in humans. Therefore, several epidemiological studies have examined the effects of mobile phone use on tumor formation. By far the most common area of focus has been on tumors of the head and neck area (e.g., gliomas, meningiomas, acoustic neuromas, and salivary gland tumors). Most of the completed epidemiological studies regarding mobile phone use and cancer incidence have been case-control studies, whereas only a few cohort studies have been performed. In case-control studies a patient with a diagnosed disease is asked to participate in the study, and after the permission is granted, he/she is often interviewed. Additionally a respective control person is sought for the study. Exposure assessment is based on either interviews or records from mobile phone network operators. If the exposure assessment is based on interviews, recall bias (i.e., how well the study person recalls the duration of phone calls, the location where the phone was held, etc.) may significantly affect the findings. The most recent large epidemiological study on mobile phone use and tumor risk has been the INTERPHONE study, which included over 5000 brain tumor cases with respective controls in 13 different countries (INTERPHONE Study Group 2010). The research group concluded that no overall increased risk of glioma or meningioma was observed due to mobile phone use. However, the

research group observed some indications of an increased risk of glioma at the highest exposure levels (long-term heavy usage), but biases, such as recall bias, and error prevented a causal interpretation. Several expert groups currently conclude that overall the studies published so far do not demonstrate a raised risk within approximately ten years of mobile phone use for brain tumors or any other head tumors. However, for slow-growing tumors the latency period is still too short to draw conclusions (e.g., International Commission for Non-Ionizing Radiation Protection (ICNIRP) 2009). Recently, a new cohort study (COSMOS) was launched in five countries to examine health risks related to long-term mobile phone use (Schüz et al. 2011) according to high priority research needs identified by the World Health Organization (WHO) (World Health Organization (WHO) 2010).

Animal studies have also been used to examine the incidence of cancer in relation to mobile phone radiation exposure. For instance, Repacholi et al. exposed transgenic mice to 900 MHz pulsed wave (PW) SAR values ranging from 0.008 to 4.2 W/kg and examined incidence of lymphoma (Repacholi et al. 1997). In this study, the lymphoma incidence increased after exposure and the authors reported that PW could enhance lymphoma formation in genetically cancer-prone mice. Subsequently, the study of Repacholi et al. was replicated by Utteridge et al. (Utteridge et al. 2002) and Oberto et al. (Oberto et al. 2007), but no increased lymphoma incidence was found. In several other studies, in which genetically wild type mouse strains have been exposed to mobile phone radiation, no increased tumor incidence has been detected (e.g., La Regina et al. 2003, Tillmann et al. 2007). Animal studies have also been used to examine whether mobile phone radiation could enhance the carcinogenicity of other agents. For example, Tillmann et al. recently exposed mice lifelong to the UMTS signal in the presence of known carcinogen and reported a doubled rate of lung cancers in the treated group when compared to the controls (Tillmann et al. 2010). The authors of this pilot study suggested that the UMTS signal might be potentially cocarcinogenic. Nonetheless, most published studies have not reported potential epigenetic carcinogenicity of mobile phone radiation (e.g., Heikkinen et al. 2006).

2.1.3.3. Human volunteer studies

Human volunteer studies can provide direct evidence of the actual human response, and several human volunteer studies have therefore been performed regarding mobile phone radiation exposure. However, due to ethical reasons, the endpoints in human volunteer studies are limited to transient physiological phenomena, such as nervous and endocrine system function or thermoregulation. Other endpoints include effects on sleep quality and symptoms of illness such

as headaches.

Nervous system studies have included, for instance, behavioral and neurophysiological measurements. These have recently been reviewed, among others, by van Rongen et al. and Kwon and Hämäläinen (van Rongen et al. 2009, Kwon, Hämäläinen 2011). A few positive findings have been reported in early behavioral studies, e.g., improved learning after mobile phone radiation exposure. Nevertheless, these findings have not been reproduced in later larger studies, even though these studies might have been performed by the same research groups (e.g., Koivisto et al. 2000a, 2000b vs. Haarala et al. 2003a, 2003b, 2004). Potential reasons for the diverse results could be the better experimental design in later studies, i.e., more study subjects, double blinding, and better control for false positives in statistical analysis.

Sleep quality has been examined in relation to mobile phone radiation exposure. Certain results suggest that mobile phone exposure has an effect on sleep electroencephalography (EEG) by increasing the EEG alpha range in the sleep EEG (e.g., Lowden et al. 2011). However, several other studies have found no effects on other sleep quality parameters (e.g., Fritzer et al. 2007, Mohler et al. 2010).

Volkow et al. exposed human volunteers to mobile phone radiation and investigated brain glucose metabolism using positron emission tomography (Volkow et al. 2011). A minor, but statistically significant, increase in brain glucose metabolism in the brain regions closest to mobile phone was reported after the exposure. Recently, Kwon et al. applied similar type of research approach as Volkow et al. (Kwon et al. 2011a, 2011b). No effects were found on cerebral blood flow, while brain glucose metabolism was suppressed after mobile phone radiation exposure. However, it is unknown whether changes in brain glucose metabolism have any clinical significance.

Some human studies *in vivo* on genotoxicity have also been performed. For example, Gandhi and Anita reported an increase in chromosomal damage when comparing mobile phone users and never-users, but the results were indicated as preliminary (Gandhi, Anita 2005). Yadav et al. reported an increased frequency of micronuclei in cells exfoliated from the human oral cavity of mobile phone users in comparison to controls (Yadav, Sharma 2008). The authors also reported a correlation between the years of exposure. Hintzsche and Stopper used a similar type of study set-up to Yadav et al. but found no differences related to mobile phone use (Hintzsche, Stopper 2010). Thus, no conclusions can yet be drawn on human genotoxicity studies. Additionally, Karinen et al. have examined molecular responses in human skin *in vivo* (Karinén et al. 2008). This study is presented in section 2.2.3.

2.1.3.4. Physiological endpoints in animal studies

In addition to cancer incidence (section 2.1.3.2), other biological and physiological endpoints have also been studied *in vivo* after mobile phone radiation exposure. Either rats or mice have most commonly been used in these experiments, but some studies have also used rabbits or flies (*Drosophila melanogaster*) as study subjects.

One of the interesting endpoints related to mobile phone radiation exposure has been the blood-brain barrier (BBB) and potential leakages in it. Possible leakages in the BBB may allow molecules of the blood circulation to enter the cerebrospinal fluid, causing potentially harmful effects. Some studies have indicated that mobile phone radiation might have an effect on BBB permeability. For example, Salford et al. reported an increase in the permeability of the blood-brain barrier to albumin after a two-hour exposure to a GSM signal (SARs 2 mW/kg, 20 mW/kg, and 200 mW/kg) (Salford et al. 2003). It was also suggested to cause neuronal damage throughout the brain, especially in the cortex, hippocampus, and basal ganglia. However, no effects on the BBB have been observed in replications of the Salford et al. study (de Gannes et al. 2009, Masuda et al. 2009). In addition, several other studies have reported no effects on the BBB (e.g., Finnie et al. 2006a). Therefore, based on the current scientific evidence, the effects on the BBB following mobile phone radiation exposure remain controversial, but seem very improbable.

Other brain areas and functions have also been examined after mobile phone radiation exposure. Recently, for example, Finnie et al. found no evidence of microglial activation (Finnie et al. 2010). In their study, they observed no perturbation of the neural tissue after acute (60 min) or long-term (2 years) exposure of mice using 900 MHz GSM with a whole body SAR of 4.0 W/kg. However, Maskey et al. reported hippocampus damage in rodents after a few months of exposure to an 835 MHz CDMA signal with an SAR range of 1.6 to 4.0 W/kg (Maskey et al. 2010a, 2010b).

Reproduction, fertility, and postnatal juveniles have recently been a concern related to RF-EMF exposure, as juveniles are subjected to a long-term exposure over their life time. At present, it is known that exposure to thermal levels of RF-EMF has a harmful impact on pregnancies and fertility (International Commission for Non-Ionizing Radiation Protection (ICNIRP) 2009). Meanwhile, the number of studies on the non-thermal level of exposure is limited, and no consistent non-thermal effects have yet been reported. For instance, Lee HJ et al. recently exposed rats to a CDMA signal at a SAR of 2 W/kg and found no effects on spermatogenesis in rats after a subchronic exposure (Lee et al. 2010). However, a few human studies *in vitro* have presented contradictory evidence (Falzone et al. 2008, 2011). Fragopoulou et al. recently detected cranial and postcranial

skeletal variations induced in mouse embryos after exposure to a commercial mobile phone (Fragopoulou, Koussoulakos & Margaritis 2010), whereas Kumlin et al., for instance, observed no morphological changes in juvenile rats (Kumlin et al. 2007). In the study by Kumlin et al., animals exposed to mobile phone radiation showed significantly improved performance in a water maze task when compared to sham-exposed animals, indicating improved learning and memory (Kumlin et al. 2007). In general, results related to reproduction and postnatal development after mobile phone radiation exposure are still sparse and, for instance, WHO has recommended studies in this field as a high priority research need (World Health Organization (WHO) 2010).

Several other physiological endpoints related to, for example, nervous, auditory, endocrine, and cardiovascular systems, and different organs have also been investigated (for a review, see e.g., International Commission for Non-Ionizing Radiation Protection (ICNIRP) 2009). Recently, for instance, Bartsch et al. examined health effects at the general level in several rat studies *in vivo* after chronic exposure to a GSM-like signal (Bartsch et al. 2010). They suggested that the chronic exposure may incur negative health effects and shorten the life span of the animals if the treatment time is sufficiently long and the observational period covers the full life span of the animals. Meanwhile, Jin et al. reported that a one-year simultaneous CDMA/WCDMA chronic exposure at a SAR of 2.0 W/kg did not increase chronic illnesses in rats, although there were some altered parameters in the complete blood count and serum chemistry (Jin et al. 2011).

2.1.3.5. Genotoxicity

Genetic effects after mobile phone radiation exposure have been widely studied. The potential presence of genotoxic effects might lead to tumor formation in the future. Several techniques have been used, such as the detection of chromosomal aberrations, sister chromatid exchanges, and micronuclei, as well as the comet assay and γ -H2AX phosphorylated histone assays. Studies both *in vivo* and *in vitro* have on this topic been published. Most of the published genotoxicity results have not reported effects. Nevertheless, some results remain contradictory (for a review, see e.g., Verschaeve 2009, Verschaeve et al. 2010).

The potential genotoxicity of RF-EMF has been studied with animals, mainly with mice or rats. For instance, in the mid-1990s, Lai and Singh reported that a pulsed 2450 MHz RF-EMF has genotoxic potential. The authors found that the number of DNA single- and double-strand breaks increased in rat brain cells after 2 hours of exposure. The effects were reported immediately after the exposure and four hours after 0.6 and 1.2 W/kg exposures *in vivo* (Lai, Singh 1995, 1996, 1997). However, neither replication studies (Malyapa et al. 1998,

Lagroye et al. 2004) nor studies using GSM exposures (Belyaev et al. 2006) have reported similar results. Furthermore, long-term exposures of mice to GSM signals have not caused increased micronuclei frequencies (e.g., Juutilainen et al. 2007, Ziemann et al. 2009). In summary, most of the animal studies have not reported direct genotoxic effects after RF-EMF exposure at non-thermal levels (International Commission for Non-Ionizing Radiation Protection (ICNIRP) 2009).

Genotoxicity has been examined *in vitro* using several different techniques. The majority of studies have not reported effects after mobile phone radiation exposure, while a few positive results concerning rather severe chromosomal effects after mobile phone radiation exposure have also been reported. For example, Tice et al. exposed human leukocytes and lymphocytes to several different mobile phone radiofrequency signals at various SAR levels (Tice et al. 2002). They reported micronuclear changes after a 24-hour exposure with all applied RF technologies at SAR averages of 5 or 10 W/kg in human lymphocytes, but not in leukocytes. After a shorter exposure time of 3 hours, no effects were observed. Using a continuous wave (CW) exposure, Mashevich et al. and Mazor et al. reported increased chromosomal aneuploidy (Mashevich et al. 2003, Mazor et al. 2008). These studies were recently repeated in part by Bourthoumieu et al. (Bourthoumieu et al. 2010, 2011). They examined the cytogenetic effects of 900 MHz mobile phone radiation on cultured amniotic cells and found no significant change in the rate of aneuploidy of chromosomes 11 and 17 or other direct cytogenetic effects. However, the exposure conditions (duration of exposure and SAR levels) were not identical. Several other studies *in vitro* have also reported no genotoxic effects (e.g., Vijayalaxmi et al. 2001a, 2001b, McNamee et al. 2002, 2003, Zeni et al. 2003, 2005, 2008, Scarfi et al. 2006, for review, see e.g., Verschaeve et al. 2010).

Many comet assay studies examining DNA damage and repair *in vitro* have also been published. Recently, an Italian research group reported that modulated GSM signals induced a significant increase in comet parameters in trophoblast cells after a 16- and 24-hour exposure at an SAR level of 2 W/kg (Franzellitti et al. 2010), while CW exposure did not. The changes were reversible after 2 hours of recovery. After shorter exposure times, no effects were observed (Valbonesi et al. 2008). Changes in the comet assay after mobile phone exposure have also been published by an Austrian research group (Diem et al. 2005, Schwarz et al. 2008). DNA strand breaks were already reported at low SAR levels in human fibroblasts. However, results of these studies have been criticized, and using the same study design the results have been negative elsewhere (Speit, Schutz & Hoffmann 2007). Most studies using the comet assay to assess DNA damage and repair have not reported any alterations in these

after mobile phone radiation exposure (e.g., McNamee et al. 2002, 2003, Hook et al. 2004, Zeni et al. 2005, 2008, for review, see e.g., Verschaeve et al. 2010).

DNA strand breaks can also be examined with a γ -H2AX phosphorylated histone assay, which is currently considered to be the most sensitive method for detecting DNA damages. So far, the method has not been widely used in mobile phone radiation research. Recently, for example, Belyaev et al. applied the γ -H2AX technique to study effects on human lymphocytes using exposures at different frequencies, signal modulations, and at an average SAR of 0.4 W/kg (Belyaev et al. 2009). The results suggested a long-lasting inhibition in the formation of DNA double-strand breaks co-localizing the 53BP1/ γ -H2AX DNA repair foci. The effect was suggested to depend on the carrier frequency, with the UMTS signal being more effective than the GSM signal.

Additionally, the genotoxicity of the mobile phone radiation has been studied in the presence of known mutagens. Recently, for example, Luukkonen et al. (Luukkonen, Juutilainen & Naarala 2010) and Sannino et al. (Sannino et al. 2009a) examined the combined effects of mobile phone radiation and a known chemical mutagen using the comet assay. Chemical treatment with the mutagen led to the induction of DNA damage, but no additional DNA damage was observed when mobile phone radiation exposure was also applied. However, another micronuclei assay study by Sannino et al. (Sannino et al. 2009b) reported an adaptive response in human lymphocytes caused by pre-exposure to 900 MHz mobile phone radiation before chemical mutagen treatment. The lymphocytes for the study were collected from different donors, and lymphocytes from only some donors responded adaptively.

2.1.3.6. Cellular effects

Different cellular effects have also been examined after mobile phone radiation exposure. The potential differences in cellular behavior might play a role, for instance, in later tumor development. These cellular effects include proliferation, differentiation, apoptosis, and transformation, as well as the expression of specific genes and proteins (section 2.1.4).

Cellular growth has been examined with several methods. Recently, for instance, Lee KY et al. found no differences in cell cycle distribution after exposure *in vitro* to the CDMA/WCDMA signal for one hour at an SAR level of 4 W/kg (Lee et al. 2011). Sekijama et al. exposed three different cell types to the WCDMA signal with different durations up to 96 hours and the SAR averages up to 0.8 W/kg and found no differences in cell growth (Sekijama et al. 2010). The ornithine decarboxylase (ODC) expression levels have also been assessed, since the enzyme is involved in cell growth and its overexpression might regulate, for instance, cancer invasiveness. In the mid-1990s, increased ODC activity

was reported after exposure *in vitro* to various frequencies and modulations of RF-EMF (Litovitz et al. 1993, Penafiel et al. 1997). The increased activity was suggested to be exposure time-, frequency- and modulation-specific, peaking at certain points (the so-called ‘window effect’). These studies have since been replicated, but no increase in ODC activity has been observed (Desta, Owen & Cress 2003, Höytö, Juutilainen & Naarala 2007). However, it has been reported that ODC activity is sensitive even to small temperature changes (Höytö et al. 2006), which could have been caused by mobile phone radiation exposure in the original study set-up. A few studies have also reported effects on cell proliferation after mobile phone radiation exposure (e.g., Velizarov, Raskmark & Kwee 1999), whereas several others have not shown effects on cell proliferation or viability (e.g., Nikolova et al. 2005, Gurisik et al. 2006, Merola et al. 2006, Sanchez et al. 2006, Chauhan et al. 2007a, Huang et al. 2008a, 2008b).

Cellular apoptosis is an important process in which mutated or otherwise damaged cells are guided to ‘commit suicide’ and thus be eliminated from the tissue. The effects of mobile phone radiation exposure on cellular apoptosis have been examined in several studies. For instance, Buttiglione et al. exposed a human neuroblastoma cell line to a 900 MHz PW at a mean SAR level of 1 W/kg. After 24 hours the authors reported an increase in apoptosis and also a decrease in known apoptosis inhibitor genes BCL-2 and survivin at the mRNA level (Buttiglione et al. 2007). Caraglia et al. also reported an increase in cellular apoptosis as well as changes in apoptosis-related genes after a 3-hour exposure to the 1950 MHz RF-EMF at an SAR level of 3.6 W/kg (Caraglia et al. 2005). However, most studies examining apoptosis after mobile phone exposure have not reported any changes (e.g., Gurisik et al. 2006, Joubert et al. 2006, 2007, Lantow et al. 2006c, Merola et al. 2006, Falzone et al. 2010).

Cellular transformation has been examined to determine whether the RF-EMF exposure could act as an inducer or a promoter of tumor formation or as a potential cocarcinogen. In the 1980s, Balcer-Kubiczek and Harrison reported that cellular transformation was increased in the presence of a known carcinogen after RF-EMF exposure (Balcer-Kubiczek, Harrison 1985, 1989, 1991). However, several newer studies have failed to support this observation. For example, Hirose et al. found no evidence of cellular transformation using the same cells as Balcer-Kubiczek and Harrison and a 2142.5 MHz WCDMA exposure (Hirose et al. 2008).

One potential mechanism that has been proposed for RF-EMF-associated effects is the ROS-mediated mechanism. ROS formation after the mobile phone exposure has consequently been examined in a few studies. Most of these have not reported any effects on ROS production after mobile phone radiation exposure alone or in combination with known chemical agents (e.g., Lantow et al. 2006a,

Brescia et al. 2009, Falzone et al. 2010, Luukkonen, Juutilainen & Naarala 2010). Thus, the current data suggest that mobile phone radiation exposure has no effect on ROS production in several different cell lines (International Commission for Non-Ionizing Radiation Protection (ICNIRP) 2009).

2.1.4. Protein and gene expression

Gene expression on the transcriptional and translation level has been widely examined following mobile phone radiation exposure. Early studies focused on examining the expression of specific genes and proteins, such as heat shock proteins, proto-oncogenes and proteins of different signal transduction pathways. Furthermore, some proteins relating to cellular structures have been examined. Subsequently, new high-throughput screening techniques, such as transcriptomics and proteomics (section 2.2.3), have also been applied in mobile phone radiation research. There have been several studies reporting both effects and no effects on protein and gene expression after mobile phone radiation exposure. These studies have recently often been reviewed (e.g., Vanderstraeten, Verschaeve 2008, International Commission for Non-Ionizing Radiation Protection (ICNIRP) 2009, McNamee, Chauhan 2009, Gaestel 2010).

2.1.4.1. Heat shock proteins

Stress proteins, i.e., heat shock proteins (HSPs), are a large group of proteins that are highly conserved and found in all cell types among different species. They function as molecular chaperones and are expressed both constitutively and in response to several different types of environmental stresses, such as heat, cold, and chemical agents. For instance, the HSP70 protein family is commonly known to respond readily to different stressors (for a review, see e.g., Lindquist, Craig 1988, Kregel 2002). Because of their nature as stress responding proteins, these proteins have been suggested to be affected by mobile phone exposure (e.g., French et al. 2001, Leszczynski et al. 2002). Thus, the expression of HSP genes has been examined in several studies *in vivo* and *in vitro* both on transcriptional and translational levels after mobile phone radiation exposure. Most of the studies carried out to date have detected no effects after mobile phone exposure on HSP expression (International Commission for Non-Ionizing Radiation Protection (ICNIRP) 2009), although some exceptions exist. The HSP studies are summarized in the text and Table 3 in Appendix 1. Additionally, a few early studies using CW exposure have been included.

Fritze et al. published one of the first studies *in vivo* examining the response of HSPs to mobile phone radiation (Fritze et al. 1997). In this study, rats were exposed to GSM and a respective CW signal. Immediately after

CW exposure of 7.5 W/kg, a slight induction of *Hsp70* mRNA was recorded in certain brain areas, but this was not observed at lower SAR values or 24 hours after the exposure. No other changes were observed, and the authors therefore suggested that acute high intensity microwave exposure may induce a minor stress response, but does not lead to lasting adaptive or reactive changes in the brain. In 2000, De Pomerai et al. reported an increase in the activity of the *Hsp16* reporter gene in *C. Elegans* after a low-level CW exposure of 750 MHz (de Pomerai et al. 2000). However, this study was later retracted, as the authors observed that the elevation of gene expression was probably due to the temperature rise during the exposure (Dawe et al. 2006). Subsequently, the same authors reported observing no increase in *Hsp16* reporter gene activity at higher exposure levels with either CW or GSM signals (Dawe et al. 2008). Weisbrot et al. examined *Drosophila melanogaster* after mobile phone radiation exposure and reported elevated HSP70 protein expression levels (Weisbrot et al. 2003). However, the exposure assessment for their study was inadequate, as the SAR values were not measured for the experimental set-up. Lee JS et al. exposed *Hsp70.1*-deficient mice for weeks to a CDMA signal at the SAR level of 0.4 W/kg (Lee et al. 2005). The expression levels of HSP25, HSP70, and HSP90 were not affected after the exposure. Sanchez et al. exposed rats to the GSM signals of 900 MHz and 1800 MHz and found no alterations in the expression of HSP25, HSC70, or HSP70 in rat skin (Sanchez et al. 2008). Finnie et al. exposed pregnant mice for a several days and examined the HSP expression in their pups (Finnie et al. 2009). HSP32 and HSP70 protein expression levels were not inducible in any mouse brains, while HSP25 protein expression showed no alterations after the exposure. Recently, Watilliaux et al. exposed developing rats for 2 hours to a GSM signal of 1800 MHz with the SAR ranging from 1.7 to 2.5 W/kg (Watilliaux et al. 2010). No effects were found on the expression of HSP60, HSC70, HSP70, or HSP90, or several glial markers after the exposure. In summary, the majority of recent studies *in vivo* examining HSP expression have not reported any effects of mobile phone radiation exposure.

Several studies *in vitro* on HSP expression have also been published. These studies have reported both effects and no effects on HSP expression levels. For instance, the following publications have described alterations in HSP expression levels. Leszczynski et al. reported a transient increase in the expression and phosphorylation of HSP27 in the human endothelial cell line EA.hy926 after a one-hour exposure to 900 MHz GSM at an SAR of 2.4 W/kg (Leszczynski et al. 2002). All changes were reversible in a few hours after the exposure. Czyz et al. observed an increase in the *Hsp70* mRNA level in mouse p53-deficient embryonic stem cells after exposure to a 1710 MHz GSM signal at SAR levels of 1.5 and 2.0 W/kg for 6 or 48 hours (Czyz et al. 2004). However,

no similar effects were found using other modulation schemes, e.g., GSM Talk modulation, or using wild type mouse embryonic stem cells. Caraglia et al. reported several changes in HSP27, HSP70, and HSP90 protein expression after exposing a human carcinoma cancer cell line to 1950 MHz RF-EMF (possible modulation of the signal was not specified) (Caraglia et al. 2005). Lixia et al. exposed human eye lens epithelial cells to a GSM signal of 1800 MHz for 2 hours at different SAR levels (Lixia et al. 2006). The authors reported an increase in HSP70 protein expression after 2 and 3 W/kg exposures, but no differences were detected in the *HSP70* mRNA level using RT-PCR. Sanchez et al. examined effects on human skin and exposed different cells and human reconstructed epidermis to a GSM signal of 900 MHz or 1800 MHz for 48 hours at an SAR level of 2 W/kg (Sanchez et al. 2006, 2007). A significant decrease in HSC70 protein expression was observed in fibroblasts after the 900 MHz exposure, but not after the 1800 MHz exposure. Additionally, a slight but significant increase in HSP70 protein expression was reported in the reconstructed epidermis after 3 and 5 weeks of culture. However, no effects on HSP27, HSC70, or HSP70 protein expression were found in keratinocytes with either of the exposures in these studies. Franzellitti et al. exposed a human trophoblast cell line to GSM and CW signals of 1800 MHz for 4 to 24 hours at an SAR of 2 W/kg and examined the *HSP70* gene and protein expression (Franzellitti et al. 2008). The authors found no differences in several members of the *HSP70* family, but inducible *HSP70C* transcript levels were altered (up or down) after certain exposure types. However, the same research group found no evidence of changes in either HSC70 or HSP70 protein or gene expression after a shorter exposure (Valbonesi et al. 2008). Yu et al. exposed human lens epithelial cells to 1800 MHz RF-EMF at various SAR levels and durations and reported a significant increase in HSP27 and HSP70 protein expression with an SAR above 2 W/kg after two hours of exposure (Yu et al. 2008). Unfortunately, the exposure assessment of this study was not reported and is thus inadequate.

However, several studies *in vitro* have reported no effects on HSP expression. Capri et al. exposed human mononuclear cells to three different modulation schemes of a 1800 MHz GSM signal with different SAR levels for 44 hours and found no changes in HSP70 protein expression (Capri et al. 2004). Lim et al. investigated the effects of mobile phone radiation on HSP expression, exposing human peripheral blood to the GSM and CW signals of 900 MHz at different SARs and durations (Lim et al. 2005). No changes were observed in HSP27 or HSP70 protein expression in human leukocytes, while a response to the heat shock exposure was observed. Vanderwaal et al. exposed two different cell lines, including the human endothelial cell line EA.hy926, to a TDMA signal of 847 MHz or a GSM signal of 1900 MHz at various SAR values and durations

(Vanderwaal et al. 2006). No alteration in HSP27 phosphorylation was observed in any of the exposure conditions, while the heat shock exposure of 41 °C or 45 °C increased HSP27 phosphorylation. Lee JS et al. exposed human and rat cells to a CDMA signal of 1763 MHz for 30 min or 1 hour at SARs of 2 or 20 W/kg (Lee et al. 2006) and reported no differences in the protein expression levels of HSP27, HSP70, or HSP90. Simko et al. exposed a human monocyte cell line to GSM and CW signals of 1800 MHz for one hour at an SAR of 2 W/kg and reported no changes in HSP70 protein expression (Simko et al. 2006). Later, the same research group also exposed several different cell types to a GSM signal at an SAR of 2 W/kg for one hour with different post-incubation times and found no changes in HSP70 protein expression (Lantow et al. 2006a, 2006b). Chauhan et al. exposed three human cell types to an intermittent 1900 MHz PW signal at average SARs of 1 and 10 W/kg for 6 hours (Chauhan et al. 2006a, 2006b). RT-PCR did not reveal any differences in the mRNA levels of *HSP27* or *HSP70* after the exposures, but changes were detected after heat shock treatment. Furthermore, the same authors found no changes in the mRNA levels of several *HSPs* after a longer lasting exposure with another cell type (Chauhan et al. 2007b). Hirose et al. examined HSP27 phosphorylation after exposing two types of human cells to a WCDMA and CW signal of 2142.5 MHz for different durations and SAR levels of up to 0.8 W/kg (Hirose et al. 2007). No differences were reported in HSP27 expression, phosphorylation or translocation. Neither were differences observed in the expression of other *HSPs* using DNA microchip analysis. Huang et al. exposed mouse auditory hair cells to a 1763 MHz CDMA signal at an SAR of 20 W/kg for various durations (Huang et al. 2008b). The authors found no effects on HSP27, HSP70, or HSP90 protein expression.

2.1.4.2. Proto-oncogenes

In addition to the *HSPs*, proto-oncogenes such as C-FOS, C-JUN, and C-MYC have been widely investigated regarding their response to mobile phone radiation exposure. These proteins function in cellular growth regulation. A mutation of these proto-oncogenes might lead to cell divisions occurring in an unregulated manner. Based on the current data, it appears that mobile phone radiation may not activate proto-oncogene expression, although some inconsistency in results still exists (International Commission for Non-Ionizing Radiation Protection (ICNIRP) 2009). The studies carried out on proto-oncogenes are summarized in the text and Table 4 in Appendix 1.

A few studies *in vivo* have examined proto-oncogene expression. Fritze et al. investigated the expression of several FOS and JUN proteins in rats after GSM exposure, with no alterations in these proteins being found (Fritze et al. 1997). In a series of studies, Finnie et al. exposed mice to a GSM signal of

900 MHz at an SAR of 4 W/kg for either a short or long period and examined C-FOS protein expression in the mouse brains (Finnie 2005, 2006b, 2007). No changes were observed in C-FOS protein expression after any of the exposure conditions. Yilmaz et al. reported no changes in BCL-2 protein expression in rat brains or testes after a one-month exposure to a 900 MHz commercial mobile phone (Yilmaz et al. 2008). Meanwhile, in two separate studies, Lopez-Martin et al. exposed rats to a GSM signal of 900 MHz for 2 hours at rather low SAR values in the presence of a chemical agent to make the rats more seizure-prone (Lopez-Martin et al. 2006, 2009). The authors reported an increase in C-FOS protein expression in different areas of the rat brain after mobile phone radiation exposure. In summary, the number of studies *in vivo* on proto-oncogene expression is currently still limited, but the majority of existing studies do not report effects on proto-oncogene expression.

A few more studies *in vitro* on proto-oncogene expression have been published. Ivaschuk et al. exposed rat pheochromocytoma cells to a TDMA signal of 836.55 MHz for 20–100 minutes with an intermittent protocol (Ivaschuk et al. 1997). The mRNA levels of *C-Fos* and *C-Jun* were examined, and *C-Jun* transcript levels were observed to have decreased after the 20-min exposure at 9 mW/cm², while the other exposure conditions had no effect on either of the genes. Goswami et al. exposed mouse embryo fibroblasts in two growth phases to an 836 MHz CW or 848 MHz CDMA signal at an average SAR of 0.6 W/kg for 24 hours or 4 days (Goswami et al. 1999). No effects were reported in proto-oncogene expression of serum-deprived cells, but the *Fos* mRNA levels increased in exponential growth phase cells during the transit to the plateau phase and in plateau-phase cells. This study was replicated by Whitehead et al., with the same cells and similar types of exposures being used with higher SARs of 5 and 10 W/kg (Whitehead et al. 2005). No effect on Fos expression was observed using RT-PCR, and the results of Goswami et al. could not therefore be confirmed. Czyz et al. investigated *C-Jun* and *C-Myc* expression simultaneously with HSP expression (Czyz et al. 2004). *C-Jun* and *C-Myc* expression were reported to be transiently up-regulated in p53-deficient cells, but not in wild type cells after exposure to 1710 MHz GSM. No effects on *Bcl-2* mRNA levels were observed. Chauhan et al. also examined *C-FOS*, *C-JUN*, and *C-MYC* expression simultaneously with *HSP* expression and found no differences in the mRNA level of these in three different cell types after an intermittent 1900 MHz PW exposure for 6 hours at SARs of 1 and 10 W/kg (Chauhan et al. 2006a, 2006b). Merola et al. detected no changes in B-MYB or N-MYC protein expression after 48 or 72 hours exposure to a GSM signal of 900 MHz at an SAR of 1.0 W/kg (Merola et al. 2006). Buttiglione et al. reported a significant decrease in the mRNA levels of *BCL-2* and survivin genes in parallel with impaired cell cycle progression in human neuroblastoma

cells after 24 hours of exposure to a GSM signal of 900 MHz at an SAR of 1 W/kg (Buttiglione et al. 2007). Del Vecchio et al. exposed rat primary neurons to a 900 MHz GSM signal at an SAR of 1 W/kg for several days and found no differences in *C-Fos* or *C-Jun* mRNA levels (Del Vecchio et al. 2009).

2.1.4.3. Signal transduction pathways and structural proteins

While HSP and proto-oncogene expression have been the most frequently examined targets after mobile phone radiation exposure, the expression of certain other proteins has also been assessed. Most of these proteins are somehow related to signal transduction pathways and regulate different cellular functions. In addition, a few studies regarding certain structural proteins and some other protein targets have been published. Several of these studies have simultaneously examined HSP or proto-oncogene expression. Currently, there are several contradictory reports on this topic and further research should be conducted, particularly addressing protein activity rather than total expression. The existing studies are summarized in the text and Table 5 in Appendix 1.

Only a few studies carried out *in vivo* on this topic have been published, including the following. Weisbrot et al. reported an increase in ELK1 phosphorylation along with increased HSP70 expression in *Drosophila melanogaster* after mobile phone radiation exposure (Weisbrot et al. 2003). The SAR levels for this study are unknown and the exposure assessment is therefore inadequate. Lee JS et al. found no changes in the expression or phosphorylation of MAPK, ERK1/2, JNK1/2, or p38MAPK in *Hsp70.1*-deficient mice after CDMA exposure for several weeks (Lee et al. 2005). Dasdag et al. exposed rats to a GSM signal of 900 MHz for months and examined brain tissues for p53 and active caspase-3 protein expression (Dasdag et al. 2009). No effect on p53 was observed, while a decrease in apoptosis was reported. Yan et al. used a commercial mobile phone to expose rats to 800/1900 MHz mobile phone radiation for several hours per day over several weeks, and reported mildly elevated mRNA levels for calcium ATP-ase, endothelin, neural cell adhesion molecule, and neural growth factor (Yan et al. 2009). Thus, the authors suggested that the potential injuries in brains might be due to mobile phone radiation exposure. However, the exposure assessment of this study had some deficiencies. Ammari et al. reported an increase in glial fibrillary acidic protein (GFAP) expression in rat brains after 900 MHz GSM signal exposure at 1.5 or 6 W/kg for several weeks, suggesting potential gliosis (Ammari et al. 2010). Currently, the number of studies *in vivo* on this topic is limited. The results have been contradictory and thus insufficient.

Studies *in vitro* have reported both effects and no effects on signal transduction pathways or certain structural proteins. For instance, the following studies *in vitro* have reported effects. Leszczynski et al. detected an increase in

p38MAPK expression after mobile phone radiation exposure along with changes in HSP27 expression and the phosphorylation status (Leszczynski et al. 2002). The inhibition of p38MAPK also blocked HSP27 phosphorylation, and it was thus speculated whether the p38MAPK stress response pathway could be a target for mobile phone radiation. Czyz et al. reported an increase in the *p21* mRNA level in p53-deficient embryonic stem cells after mobile phone radiation exposure, while no alteration was found in the *Erg-1* mRNA level (Czyz et al. 2004). Caraglia et al. noted changes in the expression and activity of several signaling proteins after exposing a human oropharyngeal epidermoid carcinoma cancer cell line to 1950 MHz RF-EMF (potential modulation of the signal was not specified) (Caraglia et al. 2005). The authors suggested the induction of apoptosis via inactivation of RAS–ERK survival signaling. Nikolova et al. exposed mouse embryonic stem cells to a 1710 MHz GSM signal and found elevated mRNA levels of *Bax* and *Gadd45* and a decrease in the neural-specific *Nurr1* mRNA level (Nikolova et al. 2005). However, the responses were not associated with any detectable changes in cell physiology. Friedman et al. reported activation of the ERK1/2 signal transduction pathway in rat and human cells after short-term mobile phone radiation exposure, while the p38MAPK and JNK1/2 pathways were not activated (Friedman et al. 2007). As a drawback, this study did not provide any SAR estimates. Buttiglione et al. examined the downstream MAPK cascades by exposing human neuroblastoma cells to a 900 MHz GSM signal for different durations at an average SAR of 1 W/kg (Buttiglione et al. 2007). Short-term exposures seemed to induce a transient increase in the *ERG-1* mRNA level with a simultaneous activation of ERK1/2, SAPK/JNK, and ELK-1. Yu et al. reported the activation of ERK1/2 and JNK1/2 after mobile phone radiation exposure, but the exposure assessment was not reported (Yu et al. 2008). Cervellatti et al. exposed human trophoblast cells to a GSM signal of 1817 MHz at an SAR of 2 W/kg for 1 hour and reported a sharp decrease in the intercellular gap junction-like structures and changes in connexin expression, localization and cellular structure (Cervellati et al. 2009). This implied effects on gap junctions following mobile phone radiation exposure. Del Vecchio et al. exposed rat primary neurons for several days to a 900 MHz GSM signal and reported an increase in beta-thymosin expression and a corresponding reduction in the number of generated neurites (Del Vecchio et al. 2009).

However, several studies reporting no effects on these proteins have also been published. For instance, Lee JS et al. reported no differences in the expression or phosphorylation of MAPKs, ERK1/2, JNK1/2, or p38 in two cell types under different exposure conditions (Lee et al. 2006). Hirose et al. exposed two different cells to a WCDMA signal of 2142.5 MHz at different SARs and durations (Hirose et al. 2006). Neither p53 protein expression nor

phosphorylation, nor p53 downstream targets were affected. Recently, Hirose et al. investigated microglial activation *in vitro* by examining the expression of an immune reaction-related molecule and cytokine production after exposure to a 1950 MHz WCDMA signal for 2 hours at different SARs (Hirose et al. 2010). No marked differences were found in the production of tumor necrosis factor-alpha (TNF-alpha), interleukin-1 beta (IL-1 beta), or interleukin-6 (IL-6). Huang et al. exposed mouse auditory hair cells to a 1763 MHz CDMA signal at an SAR of 20 W/kg for various durations (Huang et al. 2008b). The authors reported no effects on ERK, JNK, or p38 protein expression or phosphorylation. Lee KY et al. carried out a single exposure of human breast cancer cells to an 837/1950 MHz CDMA/WCDMA signal or a combination of both signals at an SAR of 4 W/kg for 1 hour (Lee et al. 2011). The levels of cell cycle regulatory proteins, p53, p21, cyclins, as well as cyclin-dependent kinases were unaffected after the exposure. Additionally, no effects on cell cycle distribution were observed.

2.1.4.4. Transcriptome

Several studies have adopted large-scale screening techniques to examine gene or protein expression after mobile phone radiation exposure. Naturally, some of the specific proteins discussed in earlier sections have also been assessed in the large-scale screening. Most of the studies in this field using high-throughput screening have so far focused on the gene expression level. Protein expression studies on this topic are presented in section 2.2.3.

Usually, transcriptomics techniques applied in mobile phone radiation research have been based on cDNA microarrays. This technology provides the possibility to screen up to several thousands of genes simultaneously, thus offering a large amount of information. Unfortunately, an insufficient number of biological and technical replicates is rather often used, and it is not therefore possible to perform appropriate statistical analysis. In some publications the results have even been based on a single hybridization without the further validation of target genes using other methods. Such results cannot be considered reliable. Three replicates would be a minimum requirement for statistical analysis. The experiments using transcriptomics are summarized in the text and Table 6 in Appendix 1.

To date only two *in vivo* microarray studies have been conducted in this research field. Belyaev et al. exposed rats to a GSM signal of 915 MHz for 2 hours at a whole-body SAR of 0.4 W/kg (Belyaev et al. 2006). The gene expression profiles in the cerebellum were obtained in triplicate, and a total of 12 genes having diverse functions were reported to be affected, with fold ratios being 1.34–2.74. However, the gene expression changes were not confirmed with any other methods. Paparini et al. exposed mice to a 1800 MHz GSM signal for 1 hour

at a whole body SAR of 1.1 W/kg and examined the gene expression in the whole brain (SAR 0.2 W/kg) (Paparini et al. 2008). Three replicates showed no changes in gene expression when using more stringent data analysis. When less stringent conditions were applied, a total of 75 genes were found to be affected (1.5–2.8 up or 0.67–0.29 down). The expression validation of 30 of these potentially affected genes with RT-PCR did not show any alterations. Thus, the authors concluded that there is no consistent indication of gene expression modulation in the whole mouse brain associated with a GSM exposure of 1800 MHz.

In addition to the studies carried out *in vivo*, transcriptomics has been applied several times in studies *in vitro*. Some of these have reported changes in gene expression, although they have often been based on an insufficient number of replicates. For instance, Pacini et al. exposed human skin fibroblasts using a commercial mobile phone (inadequate exposure assessment) for 1 hour and found 14 differently expressed genes in a single experiment (Pacini et al. 2002). Furthermore, a significant increase in DNA synthesis and intracellular mitogenic second messenger formation was reported with a matching high expression of genes in the MAP kinase family. Lee S et al. exposed a human promyelocytic leukemia cell line to a 2450 MHz PW field for 2 or 6 hours at an SAR of 10 W/kg and examined gene expression using a single replicate with the Serial Analysis of Gene Expression (SAGE) technique (Lee et al. 2005). Several hundreds of genes were reported to be affected without further validation. Remondini et al. published a pooled analysis of gene expression of several different cell types after mobile phone radiation exposure (900 or 1800 MHz) (Remondini et al. 2006). Six different cell types were exposed with various exposure protocols (SARs 1–2.5 W/kg, durations 1–44 hours). The cellular RNA was pooled from several experiments, but only a single hybridization was performed for each cell type. The cell responses varied based on the exposures and cell types, e.g., the EA.hy926 cells responded to the 900 MHz GSM exposure but not to the 1800 MHz GSM exposure, while some other cells did not respond at all to the mobile phone radiation exposure. In general, the authors suggested that some human cell types might alter their gene expression in response to mobile phone radiation, but no consistent signature (e.g., stress response) could be detected. Zhao TY et al. exposed mouse primary neurons and astrocytes to a commercial mobile phone (inadequate exposure assessment) for 2 hours (Zhao, Zou & Knapp 2007). The authors found Caspase-2,-6 and *Asc* to be affected in both cells as well as *Bax* in the astrocytes in the duplicate array analysis. The results were validated with RT-PCR. The authors suggested that a relatively short-term mobile phone radiation exposure can up-regulate the elements of apoptotic pathways in brain-originated cells. They also suggested that the neurons appeared to be more sensitive than the astrocytes. Zhao R et al. exposed rat

neurons to an intermittent (5 min on/10 min off) GSM signal of 1800 MHz for 24 hours at an SAR of 2 W/kg (Zhao et al. 2007). A single experiment displayed in total 34 altering genes with rather low fold ratios of 1.15–1.62. The affected genes were associated with multiple cellular functions, such as the cytoskeleton, signal transduction pathways, and metabolism. Most of the changes were further validated with RT-PCR.

However, several transcriptomics studies *in vitro* have not reported effects on gene expression. These findings have often been based on a higher number of replicates or further validation of potentially affected genes. For instance, Whitehead et al. exposed a non-osteogenic mouse pluripotent cell line to two different signals for 24 hours at an SAR of 5 W/kg (Whitehead et al. 2006a, 2006b). Three replicates displayed differences (fold ratio >1.3) in several genes, but based on the sham-sham and false positive rate calculations, the authors concluded that the number of affected genes after the exposure did not exceed the false-positive rate, and no differences were therefore actually observed. In the positive control the number of affected genes was higher than the false positive rate. However, none of the potential target genes for the mobile phone radiation exposure were confirmed with any other methods, as they were solely rejected based on the false positive rate calculations. Qutob et al. and Chauhan et al. exposed a human glioblastoma-derived cell line and human monocyte-derived cell line to a 1900 MHz PW signal for various SAR values and durations (Qutob et al. 2006, Chauhan et al. 2007b). In the data analysis a gene appearance in all five performed replicates was required. No evidence of effects due to mobile phone radiation was found, while several affected genes were found in the positive control samples (heat shock). In addition, several *HSP* genes were confirmed to be unaffected by RT-PCR, and thus confirmed to be actual false negatives, as in the microarray results. Hirose et al. exposed human glioblastoma cells and human fibroblasts to various signals, durations, and SAR levels (Hirose et al. 2006, 2007). Two experiments showed no consistent effects after mobile phone radiation exposure, and the expression of p53-related genes was further confirmed not to be affected by RT-PCR. Zeng et al. exposed a human breast cancer cell line to a GSM signal of 1800 MHz at average SARs of 2 and 3.5 W/kg for 24 hours using an intermittent exposure (5 min on/10 min off) (Zeng et al. 2006). Five potentially responding genes were found after the exposure of 3.5 W/kg in the duplicate analysis. However, RT-PCR did not confirm the differences in these genes, and the authors therefore suggested that no effects were actually observed. Gurisik et al. exposed a human neuroblastoma cell line to a 900 MHz GSM signal for two hours at an SAR of 0.2 W/kg, allowing a recovery time of two hours afterwards (Gurisik et al. 2006). Six genes were found to be slightly down-expressed in a single experiment. The expression of two of these

genes was further validated with RT-PCR, but no confirmation for the array results was obtained. Thus, the authors suggested that no effects were observed due to the exposure. Huang et al. exposed mouse auditory hair cells and human T lymphoma cells to a CDMA signal of 1763 MHz with various SAR levels and durations (Huang et al. 2008a, 2008b). A few dozens of genes were found to be affected in the analysis using either three or five replicates. However, the fold ratios were small and no consistent groups of functional categories were found in the analysis. Without any further validation, the authors suggested that the results might also be false positives and that the exposure had no effect on the global gene expression of the cells examined. Sekijima et al. investigated gene expression in three cell types after exposure to various signals and SAR levels for 96 hours (Sekijima et al. 2010). The duplicate hybridizations suggested that mobile phone radiation exposure had only a minor effect ($p < 0.05$, max fold ratio 1.14) on two cell types with the highest SAR value used, while the heat shock treatment caused changes in several genes. Therefore, the authors concluded that exposure to mobile phone radiation is unlikely to cause a general stress response in the tested cells under these conditions.

2.1.5. Conclusions based on the review of the literature

Mobile phones generate a modulated radio frequency field, which is a form of non-ionizing radiation. Mobile phone radiation does not have enough energy to cause ionizations and to induce direct chemical changes (e.g., DNA strand breaks). Currently, it is not known whether mobile phone radiation might cause other than thermal effects, and potential mechanism for such effects is unknown.

During the past two decades, a considerable amount of research has been conducted related to the biological and health effects of mobile phone radiation exposure. Several biological and medical endpoints have been addressed in these studies. In general, the results in this field have been contradictory. Most of the studies published to date have not reported any effects after mobile phone radiation exposure, but certain studies have reported such effects. Furthermore, attempts to repeat some of the earlier experiments suggesting effects have not reported similar findings.

For instance, it seems that mobile phone radiation has no immediate carcinogenic risk at low SAR levels, whereas knowledge of the effects of long-term use (over ten years) is still limited (International Commission for Non-Ionizing Radiation Protection (ICNIRP) 2009). Based on the current scientific knowledge on tumor formation in humans or animals, at the end of May 2011, the International Agency for Research on Cancer (IARC) classified radio

frequency electromagnetic fields as possibly carcinogenic to humans (Group 2B) (Baan et al. 2011). This classification was based on the increased risk of glioma associated with mobile phone use found in some studies, and coffee, for instance, belongs to the same class. Human volunteer studies have shown consistent effects on thermoregulatory systems after RF-EMF exposure (for a review, see e.g., International Commission for Non-Ionizing Radiation Protection (ICNIRP) 2009), which have been due to the RF-EMF-induced heating. Other human volunteer studies have led to no response or inconsistent responses following mobile phone radiation exposure (behavioral studies, neurophysiological studies). Various endpoints have also been examined *in vivo* and *in vitro*. A large majority of studies with different cellular endpoints or genotoxicity have reported no effects after exposure, although some of the publications have suggested changes after mobile phone radiation exposure. However, different biological systems, exposure set-ups and conditions have been applied in these studies, and comparison of the results is therefore not always straightforward.

Based on the gaps in current knowledge, the World Health Organization has identified specific research needs in this field (World Health Organization (WHO) 2010). These high priority research needs include epidemiological cohort studies on children and adolescents as well as RF-EMF exposure provocation studies on human volunteers, including children of different ages. Emphasis on juveniles has also been addressed via animal studies focusing on early-life and prenatal RF-EMF exposures.

2.2. Proteomics

2.2.1. Overview

Proteomics refers to the large-scale study of proteins, their structures, functions, and modifications, as well as their interactions with each other. The technology allows simultaneous screening of several hundreds, even thousands, of proteins and thus enables, for instance, biomarker discovery in different clinical or pathological conditions and various types of systems biology approaches. A basic proteomic analysis is focused on analytical protein chemistry by characterizing proteins and their post-translational modifications (e.g., phosphorylation, methylation, glycosylation, ubiquitination). In expression proteomics, i.e., differential display proteomics studies, the protein expression profiles are examined using a case-control experimental set-up. Proteomics is also used to examine protein–protein interactions and identify protein complexes. (Simpson 2002)

The field of proteomics has rapidly expanded over the past two decades. The words “proteome” and “proteomics” were introduced in the mid-1990s, although the principal technologies used existed before that. According to the original definition, a proteome meant the total protein complement of a genome (Wasinger et al. 1995). Since then, the term proteome has also been widely used to describe the set of proteins that are expressed during a certain time under given environmental conditions, and the total protein complement has been termed a complete proteome.

The core technique for proteomics studies was originally two-dimensional gel electrophoresis (2DE), which was developed in the 1950s (Smithies, Poulik 1956) with further significant developments in the 1970s (O’Farrell 1975, Klose 1975, Garrels 1979). In the 1990s, mass spectrometry (MS)-based techniques for proteomics studies were also developed. In MS studies, unlike in 2DE studies, the protein identity is obtained immediately and the protein expression levels can be compared between samples if labeling is used. Nowadays, several different techniques based on heavy and light stable isotopic labeling (e.g., ICAT, iTRAQ, SILAC) can be used for MS/MS-driven proteomics studies. However, MS studies also have limitations, mostly related to instrument requirements and data analysis. Proteomics can additionally be used to examine protein interactions, e.g., with (yeast) two-hybrid systems by engineering a host organism to express a protein of interest.

In general, these screening techniques, which are used in parallel, create a massive amount of data and thus require sophisticated analysis methods and programs, which have remained a challenge. Additionally, proteome-wide measurements with standard shotgun techniques (2DE, MS) only provide information about those proteins that are expressed in the cell at a specific time, while information about protein dynamics (e.g., half-lives) is not accessible (Wilkins 2009). Some of the typical problems in high-throughput studies were addressed by a group of experts as they developed guidelines for proteomics publications (Wilkins et al. 2006). In addition to these high-throughput techniques, specific and comprehensive serial applications for certain model organisms also exist, such as organism engineering for protein tagging and comprehensive antibody arrays. Often, these serial applications provide higher-quality data concerning abundance, half-life, and localization of proteins, but unfortunately they are only useful for specific model organisms that can be genetically manipulated. However, high-throughput techniques are currently the most capable techniques to provide different insights in case-control set-ups, especially for genetically non-engineered organisms. (For a review, see e.g., Wilkins 2009.)

2.2.2. Two-dimensional gel electrophoresis

2.2.2.1. Principles

Two-dimensional gel electrophoresis (2DE) was invented in the 1950s and several marked improvements have been introduced since then (for a review, see e.g., Görg et al. 2009, Klose 2009). Since the 1990s, 2DE has been widely applied in proteomics studies. In 2DE, proteins are separated from each other based on their charge, i.e., the isoelectric point (pI) of the protein and the molecular weight (MW) (Simpson 2002, Westermeier 2005).

Sample preparation is a crucial step in 2DE. Typically, a sample requires preparative steps before it can be applied in 2DE. Proteins can be extracted from simple cellular samples with different lysing techniques, such as sonication, freeze and thaw, or detergent lysing in the presence of protease inhibitors. More complex samples might also require cleaning or precipitation. In certain applications, sample fractionation based on, for instance, cellular components or molecular weight is useful.

In the first-dimension separation the protein charge is neutralized in a gradient pH gel using high voltage isoelectric focusing (IEF). Earlier, carrier ampholytes IEF was performed, but nowadays immobilized pH gradient gels (i.e., the IPG strips) are typically applied. IPG strips allow high reproducibility and enable protein separation with various wide and narrow pH ranges. For proteins having very basic isoelectric points, non-equilibrium pH gradient electrophoresis (NEPHGE) can also be applied.

The second-dimension separation is based on the molecular weight, often using standard sodium dodecyl sulphate polyacrylamide gel electrophoresis (SDS-PAGE) (Laemmli 1970), although other buffer systems have also been developed. The used gels are either single percentage gels (e.g., 10% or 12%) or gradient gels (e.g., 4–20%), depending on the appropriate molecular weight range. Either lab-made or commercial gels can be used.

Protein detection is based on either protein labeling before electrophoresis separation or post-staining of gels. Radioactive labeling with ^{35}S or ^{32}P is a very sensitive technique and stable isotopes $^{14}\text{N}/^{15}\text{N}$ or $^{12}\text{C}/^{13}\text{C}$ are useful for quantitative analysis. However, these techniques require a living sample and are thus not applicable for biopsy samples. Additionally, radioactive labeling requires facilities to handle radioactive material. Proteins can also be labeled with fluorescent dyes (Cy dyes), which has become a state-of-the-art technique in 2DE. Post-staining of gels can be performed with several techniques, e.g., with coomassie blue, silver, or fluorescent dyes, each of which have different advantages and limitations. Coomassie blue staining is the easiest to use but not very sensitive. Silver staining is sensitive but requires several steps and is

not linear. Fluorescent dyes are linear but often expensive. Additionally, stains detecting special modifications, such as phosphorylation, are commercially available. (See further discussion in section 2.2.2.2.)

The gels with visualized proteins are imaged, usually with high resolution (laser) scanners or specific cameras. For differential display proteomics studies, 2DE gel maps are analyzed with specific computer software. The software is designed to quantitatively analyze protein expression profiles in gels and also perform statistics. Proteins of interest can be identified using MS technologies. The simplest MS identification is based on peptide mass fingerprinting (PMF), in which proteins are digested with a specific enzyme to generate peptides. Peptide masses are compared to databases to identify the proteins. Amino acid sequencing can also be performed to obtain an exact sequence using MS/MS instruments. After MS identification, special applications and further studies can be applied to proteins of interest.

2.2.2.2. Challenges and recent developments

Currently, 2DE is the most widely applied technique for proteomics studies. It is highly parallel, allowing several gels to be run simultaneously, and it enables the separation of several hundreds of proteins in a single gel. Furthermore, protein abundances are immediately available, as well as post-translational modifications based on the change in the pI of the protein. However, the 2DE technique also has limitations and challenges in the analysis of certain types of proteins (Görg et al. 2009). Proteins having an extreme pI (very acidic or alkaline) have usually been considered a challenge for two-dimensional separations, but nowadays several solutions have been introduced to overcome these problems, e.g., the narrow interval IPG strips (down to pH 2.5 for acidic proteins and up to pH 12 for alkaline proteins), specific reagents to stabilize the cysteine sulfhydryl groups in alkaline proteins, specific sample application techniques, and the application of high voltages (up to 12 000 V) (for a review, see e.g., Görg et al. 2009). Membrane proteins constitute a significant proportion of a cell's protein content, but are still underrepresented in 2DE gels. Because of their hydrophobic nature, the solubility of the membrane proteins is poor and they tend to aggregate and precipitate in aqueous media. Some potential modifications to the solutions used have been described (for a review, see e.g., Görg et al. 2009). It seems that no single proteomics technology currently exists to separate the complete membrane proteome, and membrane proteins therefore need to be investigated using a combination of several techniques. Additionally, the low abundance proteins are a major problem for all proteomics analysis technologies. The problem can be approached by targeting specific sub-proteomes (e.g., the isolation of certain cellular components using cellular

fractionation) or by applying sample prefractionation methods (e.g., preparative IEF, free-flow electrophoresis) simultaneously with various narrow pH gradient IPG strips, and thus allowing higher protein loads. Several of these protein classes, whose analysis in a simple total cell lysate 2DE is limited, are targets of growing interest in specific applications. This emphasizes the importance of an appropriate experimental design in studies in which the study hypothesis is based on the investigation of these proteins.

Protein visualization is one of the crucial steps for accurate data analysis and for protein abundance determination. Coomassie blue staining has been used for a long time for protein detection in 2DE. However, the limited sensitivity of this staining restricts the detection of even moderately abundant proteins. Silver staining with several different modifications has also been widely applied in 2DE analysis. Silver staining is one of the most sensitive staining methods for certain proteins, but problems arise from its limited linear dynamic range. Nowadays, it is generally accepted that less than two-fold differences cannot be detected using silver staining because of linearity problems. Thus, fluorescent dyes, such as Sypro® Ruby, with a high linearity have been introduced. In the late 1990s, Unlü et al. described a technique called difference gel electrophoresis (DIGE) utilizing fluorescent Cy dyes for protein labeling (Unlü, Morgan & Minden 1997). Three dyes with similar molecular weights but distinct fluorescent characteristics were developed. The dyes react with either lysine amino acids (minimal labeling) or cysteines (saturation labeling) and preserve the charge of the target amino acid. Proteins are labeled with dyes before electrophoretic separation and a pool of proteins labeled with three different dyes can be separated in a single gel. The technique was further developed by Alban et al. as a common internal standard was applied to all electrophoretic separations (Alban et al. 2003). This internal standard was used for data normalization and it was shown to greatly improve data analysis. Protein abundances were better controlled and technical variation diminished, as the same standard sample was run in all gel separations, enabling better gel-to-gel analysis. So far, DIGE has become a state-of-the-art technique in differential display 2DE studies, as the three fluorescent dyes and the application of an internal standard provide better accuracy than other technologies. However, the technique is rather expensive, and is not therefore included among the essential methods in all laboratories.

As in all fields of science, good experimental design is crucial in proteomics for a successful study. The use of proteomics is still restricted because of several limitations, such as its technical complexity and the high cost of data production (reagents, instruments, time), all of which have contributed to a poor experimental design in several published proteomics studies (Wilkins et al. 2006). In recent years, particular attention has been paid to experimental

design and data analysis methods in differential display proteomics studies (e.g., Wilkins et al. 2006, Karp, Lilley 2007, Minden et al. 2009). Earlier, most of the 2DE-based proteomics studies relied on the fold ratios in data analysis. However, fold ratio analyses ignore both biological and technical variations in samples, as they are based on the average fold ratios over the experimental groups, and thus increase the risk of selecting variable proteins due to the sample selection and not due to the experimental conditions. Nowadays, statistical testing, most often the Student's t-test, has been applied in 2DE data analysis to assess the nature of the observed differences, as the variance is then better controlled. However, it must be kept in mind that all statistical tests are based on certain assumptions that need to be recognized. For instance, the commonly used Student's t-test assumes a normal distribution of the data. This is not usually the case for 2DE data, as they are frequently skewed. However, this issue can be approached with appropriate data transformation methods (for reviews, see e.g., Karp, Lilley 2007, Minden et al. 2009). Another possibility is to use non-parametric tests (e.g., the Mann-Whitney U-test), which are more robust but less powerful in detecting changes. Another problem arising from statistical analysis is multiple testing (for reviews, see e.g., Karp, Lilley 2007, Karp et al. 2007). Multiple testing leads to the finding of false positives (e.g., in a typical analysis of 1000 spots at the 95% confidence level, 50 false positives may be expected due to multiple testing). This problem can be approached in several ways. Probably the most commonly used method in the proteomics field is the application of false discovery rate (FDR) correction. The focus in this method is on achieving an acceptable ratio of true and false positives. For example, a 5% FDR means that on average 5% of the changes identified as significant can be expected to be actual false positives. Recently, 2DE studies have applied both statistical testing and fold ratio analysis, which seems to be an appropriate methodology for the data analysis.

To achieve successful results from the data analysis, it is essential to consider the experimental design and the number of replicates. To date, many experiments that have used 2DE have had a low number of biological and/or technical replicates, while in certain MS/MS-driven studies the results have sometimes even been based on a single experiment, limiting the information that can be gained. Technical replicates are useful when the system includes a high level of noise, but most often the biological replicates provide more information about true effects. As the DIGE technique significantly reduces technical variation, it is usually enough to consider the number of biological replicates in 2DE-DIGE studies. The number of replicates needed has been estimated in a few studies (Karp, Kreil & Lilley 2004, Karp, Lilley 2007, Karp et al. 2007, Stühler et al. 2006). If technical variation is the only source of variation, three to five replicates are needed to determine a fold change of 1.5–2. However, if the

biological variation exceeds the systematic variation, the number of biological replicates needs to be increased respectively. For instance, the biological variation in animal studies is higher than in cell culture studies (Karp et al. 2007, Meyer, Stühler 2007). Among studies carried out *in vitro*, cell line experiments have shown less variation than primary cell cultures (Molloy et al. 2003).

Some limitations have also been identified in the DIGE system itself. For instance, preferential labeling has been observed (Tonge et al. 2001, Karp, Griffin & Lilley 2005), as well as a biased background for different dyes (Karp, Kreil & Lilley 2004). However, these problems can be overcome by using the dye-swap protocol, i.e., in the typical DIGE experiment an internal standard is labeled with the Cy2 dye and the cases and controls with the Cy3 and Cy5 dyes, swapping the dyes between the sample groups. Additionally, it has been suggested that the three-dye approach is not completely independent of the means of statistical testing, as the same internal standard is used for two samples, thus causing bias in the analysis (Karp et al. 2007). This was suggested to be resolved using only a two-dye approach.

In spite of its limitations, 2DE is the most commonly applied protein separation technique in proteome research (Görg et al. 2009). All available proteomics analysis technologies show specific technical advantages, but also have limitations. In comparison with MS/MS studies, 2DE studies require less hardware and are thus easily available for research groups. The protein abundances and post-translational modifications observed as the pI shift (e.g., protein phosphorylation and glycosylation) are initially available. Furthermore, the method is highly parallel, as several gels can be run simultaneously. With an appropriate experimental design, 2DE is a very powerful tool to reveal the protein content of the organism in certain conditions. However, none of the current proteomics technologies alone is able to address all research needs. Thus, the combination of several techniques is the most effective approach to solve the experimental question addressed.

2.2.3. Proteomics in mobile phone radiation studies

Despite the fact that proteomics has been applied extensively in several fields of research, its use in mobile phone radiation research has remained minor. To date, ten articles have been published reporting proteome responses after mobile phone radiation exposure. Four of these articles are presented in this thesis, and six of the ten proteomics studies have been performed at STUK. The proteomics studies related to mobile phone radiation exposure have been summarized in the following table (Table 1) and in the text.

Table 1. Proteomics studies after mobile phone radiation exposure.

Reference	Study material	Frequency, modulation SAR Time points (exposure/sampling)*	Proteomics technique	Results
Leszczynski et al. 2002	Human endothelial cell line EA.hy926	900 MHz GSM 2.4 W/kg 1 hr	2DE, silver staining and 32 P-labeling, Western blotting, 4 replicates for 2DE	<ul style="list-style-type: none"> • Increase in the total protein phosphorylation level • Increase in the HSP27/P-HSP27/ p38MAPK protein expression
Nylund & Leszczynski 2004 (II)	Human endothelial cell line EA.hy926	900 MHz GSM 2.4 W/kg 1 hr	2DE, silver staining, Western blotting, immunocytochemistry 10 replicates	<ul style="list-style-type: none"> • 38 proteins statistically significantly affected, 4 protein spots identified (2* vimentin, IDH3A, HNRNP1) • Changes in vimentin expression confirmed with Western blots and immunocytochemistry
Zeng et al. 2006	Human breast cancer cell line MCF-7	1800 MHz GSM, continuous and intermittent (5 min on/10 min off) 3.5 W/kg 1, 3, 6, 12, 24 hrs	2DE, silver staining, 3 technical replicates from a single protein lysate	<ul style="list-style-type: none"> • No changes observed (a few changes in all conditions, no overlap between exposure conditions, authors concluded effects as random)
Nylund & Leszczynski 2006 (III)	Human endothelial cell line EA.hy926 and EA.hy926v1	900 MHz GSM 2.4 W/kg 1 hr	2DE, silver staining, 10 replicates	<ul style="list-style-type: none"> • 38 proteins statistically significantly affected in EA.hy926, 45 proteins statistically significantly affected in EA.hy926v1, no correlation between cell line variants • No identifications or further confirmation
Li et al. 2007	Human lens epithelial cells HLEC	1800 MHz GSM 1, 2, 3.5 W/kg 2 hrs	2DE, silver staining, 3 replicates	<ul style="list-style-type: none"> • 4 proteins changed (>3-fold in 3.5 W/kg, >2-fold in 2.0 W/kg, no effect on 1 W/kg), identified as hnRNP K and HSP70 • No further confirmation
Karinen et al. 2008	Human skin, exposure <i>in vivo</i>	900 MHz GSM 1.3 W/kg 1 hr	2DE, silver staining, 10 volunteers	<ul style="list-style-type: none"> • 8 proteins statistically significantly affected • No identifications or further confirmation

*Sampling immediately after exposure unless otherwise stated

Table 1. Continued.

Reference	Study material	Frequency, modulation SAR Time points (exposure/sampling)*	Proteomics technique	Results
Nylund et al. 2009 (IV)	Human endothelial cell line EA.hy926	1800 MHz GSM 2.0 W/kg 1 hr	2DE, silver staining, western blotting 10 replicates	<ul style="list-style-type: none"> 8 proteins statistically significantly affected, 3 proteins identified (SRM, GRP78, PSA1) WB validation failed for the GRP78 protein expression No effects on HSP27 or vimentin protein expression (2DE/WB)
Gerner et al. 2010	Human T-lymphocyte cell line Jurkat T, Human primary diploid fibroblasts ES1 cells, Human peripheral blood mononuclear cells WBC	1800 MHz GSM intermittent (5 min on/10 min off) 2 W/kg 8 hrs	2DE, ³⁵ S-labeling, fluorescent dye, cytoplasmic fraction 3 replicates	<ul style="list-style-type: none"> Jurkat T cells: No differences in total protein expression, significant increase in <i>de novo</i> synthesis (³⁵S-labeling), 14 proteins identified (including, e.g., HSPs, T-complex proteins) Fibroblasts: increase in protein synthesis, 17 proteins identified (including, e.g., HSPs, T-complex proteins, annexins, BIP) WBC: minor increase in activated cells, increase in HSP60 synthesis, no effects on quiescent cells No further confirmation for any proteins
Kim et al. 2010	Human breast cancer cell line MCF-7	849 MHz CDMA 2, 10 W/kg 1 hr/day, 3 days sampling 24 hrs afterwards	2DE, silver staining, Western blotting, RT-PCR, 3 replicates	<ul style="list-style-type: none"> No reproducible changes observed Changes in GRP78, PIN1, and glucosidase II observed in single gels, but no confirmation was observed with WB/RT-PCR
Nylund et al. 2010 (V)	Human primary umbilical vein endothelial cells HUVEC, Human primary brain microvascular endothelial cells HBMEC	1800 MHz GSM 2.0 W/kg 1 hr	2DE-DIGE, 13 replicates for HUVEC, 11 replicates for HBMEC	<ul style="list-style-type: none"> No effects on either of the cell types after exposure (numerous differences between the cell types)

*Sampling immediately after exposure unless otherwise stated

Pioneering work in proteomics and mobile phone radiation research was published by Leszczynski et al. (Leszczynski et al. 2002). In this study the human endothelial cell line EA.hy926 was exposed to a GSM signal of 900 MHz at an average SAR of 2.4 W/kg for one hour. An increase in the general protein phosphorylation level was reported immediately after exposure using the ^{32}P -labeling of samples and the 2DE separation of proteins. Furthermore, a transient increase in HSP27, P-HSP27 and p38MAPK expression levels was also reported. The study was performed using four replicates and also included Western blots and immunocytochemical staining of selected proteins. Publications (II–V) by the same research laboratory are discussed in detail in this thesis.

Zeng et al. exposed the human breast cancer cell line MCF-7 to an 1800 MHz GSM signal at an average SAR of 3.5 W/kg for 1, 3, 6, 12, and 24 hours by using both continuous and intermittent exposure (5 min on/10 min off) (Zeng et al. 2006). The protein expression was studied immediately after the end of the exposures. Three silver-stained 2DE gels were prepared from a single cell lysate. A few changes, based on the fold ratio between the sample groups (2-fold up or down) or *de novo* synthesis, were observed in the analysis, but there was no correlation between the exposure conditions. The authors also performed a transcriptomics analysis for the cells exposed for 24 hours at average SARs of 2 and 3.5 W/kg and found five potentially affected genes. However, RT-PCR did not confirm differences in these genes after mobile phone radiation exposure. Thus, the authors suggested that the observed effects in the proteomics and transcriptomics analysis might have occurred by chance and were not caused by the exposure.

Li et al. exposed the human lens epithelial cells (HLEC) to a GSM signal of 1800 MHz at average SARs of 1, 2, and 3.5 W/kg for 2 hours and examined the protein expression immediately after the exposure (Li et al. 2007). The proteins were separated in triplicate silver-stained 2DE gels. In total, 4 proteins appeared with altering expression levels (>3-fold at 3.5 W/kg, >2-fold at 2.0 W/kg, no effect at 1 W/kg, no statistical testing or analysis of variances). Two of these proteins were identified as hnRNP K and one as HSP70, and the identification of one protein was not successful. The expression of these proteins was not validated with any other methods.

Gerner et al. exposed several human cells (the human T lymphocyte cell line Jurkat T, human primary diploid fibroblasts ES1 cells, human peripheral blood mononuclear cells WBC) to a GSM signal of 1800 MHz at an average SAR of 2 W/kg for 8 hours (additionally, for 2 and 4 hours) using an intermittent exposure (5 min on/10 min off) (Gerner et al. 2010). The protein expression from the cytosolic fractions was examined in triplicate immediately after exposure using 2DE with ^{35}S -labeling and fluorescent dye. Several changes were reported

in protein synthesis (^{35}S -labeled proteins) based on one-way analysis of variance (ANOVA, $p < 0.05$), while the fluorescently labeled total proteins displayed no alterations. Fourteen proteins were identified to have an altered protein synthesis level from the Jurkat T cells and a few more proteins from the fibroblasts. These identified proteins included for instance HSP-family proteins, T-complex proteins, annexins and BIP. In white blood cells (WBC), a minor increase in *de novo* synthesis was observed in the activated cells but the fold ratio was over 2 only for HSP60. No effects were observed in the quiescent white blood cells. The authors suggested that a sufficiently long time is needed to observe the effects, as there were no effects after 2- and 4-hour exposures. Additionally, it was suggested that proliferating cells with high protein synthesis rates are more sensitive to the mobile phone radiation exposures than the non-active cells.

Kim et al. exposed the human breast cancer cell line MCF-7 to a CDMA signal of 849 MHz at average SARs of 2 and 10 W/kg (Kim et al. 2010). The cells were exposed for 1 hour per day on 3 consecutive days and the cells were collected 24 hours afterwards. The protein expression was examined from three replicates using silver-stained 2DE gels. No reproducible changes were observed between these three replicates (the analysis method was not clarified), but a few proteins were found to have an altered expression level in single gels. These proteins were identified as GRP78, PIN1, and glucosidase II. Western blotting and RT-PCR were performed for these proteins, but no changes were observed, and no effects were therefore recorded in this system.

So far, a single human volunteer study *in vivo* has been published that examined the proteome effects after mobile phone radiation exposure. Karinen et al. exposed an area of the forearm skin of 10 human female volunteers to a GSM signal of 900 MHz at an average SAR of 1.3 W/kg for 1 hour (Karinen et al. 2008). Immediately after the exposure, punch biopsies were collected from the exposed area, while the non-exposed forearm served as a control. Extracted proteins were separated using silver-stained 2DE gels as a single gel per lysate. In total, 8 proteins were found to be altered in statistical tests (ANOVA and Wilcoxon tests without correction for multiple comparisons). Two of the proteins were present in all ten volunteers, while the others were expressed in 4–8 cases. However, none of the proteins was identified and their expression was not further validated. The authors suggested that mobile phone radiation exposure might alter protein expression in the human skin.

As noted, the availability of proteomics studies related to the effects of mobile phone radiation exposure is currently very limited. The 2DE technique has been applied in all ten published articles, while not a single research article has applied MS-based proteomics techniques in mobile phone radiation-related research. Additionally, most of the studies have had limitations in the

experimental design, especially in the number of replicates in relation to the staining technique used.

3. Aims of the Present Study

The general aim of the study was to examine changes in the proteome of human endothelial cells after short-term exposure to mobile phone radiation. The specific aims were to:

- Apply new genome-wide screening techniques, i.e., proteomics for the screening of several protein targets simultaneously responding to mobile phone radiation exposure. The finding of potential target proteins would allow the formulation of hypotheses of potential mechanisms by which mobile phone radiation could affect biological systems. (I)
- Investigate potential target proteins for short-term exposure to mobile phone radiation and the potential effects of mobile phone radiation on the cellular proteome. (II–V)
- Examine whether the proteome response to mobile phone radiation varies depending on the different backgrounds of the model system. (III, V)
- Examine whether the response to mobile phone radiation depends on different GSM systems/frequencies. (II, IV)
- Apply methodological development to the examined model system and experimental design to improve the data quality. (V)

4. Materials and Methods

The experimental methods used in this study are listed in Table 2 and brief descriptions of the methods are presented below. Detailed descriptions of the techniques are provided in the original publications (I–V).

Table 2. Methods used in this study.

Method	Publication
Cell culture EA.hy926/EA.hy926v1	I–IV/III
Primary cell cultures HUVEC & HBMEC	V
900 MHz GSM mobile phone radiation exposure	I–III
1800 MHz GSM mobile phone radiation exposure	IV, V
Two-dimensional gel electrophoresis, 2DE	I–V
MS identification	II, IV
Western blotting	II, IV
Immunocytochemistry	I, II

4.1. Cell cultures

In this thesis, human endothelial cells were used as a model system. Both a human endothelial cell line and primary human endothelial cells were used. Human endothelial cells were selected as a model system, because the endothelium is present in several body parts that are exposed to mobile phone radiation in everyday life. Specifically, endothelium is present in the blood-brain barrier, the function of which has been speculated to be affected, and is therefore often examined after mobile phone radiation exposure (see section 2.1.3.4).

4.1.1. Human endothelial cell line

The human endothelial cell line EA.hy926 was established by fusing primary human umbilical vein cells (HUVEC) with a thioguanine-resistant clone of the lung carcinoma cell line A549 by the exposure to polyethylene glycol (PEG) (Edgell, McDonald & Graham 1983). Hybrid clones were selected in HAT medium and screened for factor VIII-related antigen (Edgell, McDonald & Graham 1983), and the cell line was shown to exhibit typical characteristics of endothelial cells (van Oost et al. 1986, Edgell et al. 1990, Ahn et al. 1995). The EA.hy926 cell line was donated by the laboratory of Dr Cora-Jean S. Edgell of the University of North Carolina at Chapel Hill, NC, USA in 1987, and since

then it has been maintained at the University of Helsinki and at STUK. Another batch of a cell line that had been generated by subcloning of the EA.hy926 cell line was obtained from Dr Edgell's laboratory in 2000. This new batch of the cell line is referred to as EA.hy926v1.

Both of the cell lines were grown in Dulbecco's MEM (DMEM), supplemented with antibiotics, 10% fetal bovine serum, L-glutamine and HAT supplement. For the mobile phone radiation experiments, the cells were removed from the culture flasks by brief trypsinization, washed in cell culture medium and seeded to specific Petri dishes designed to be used in the exposure set-ups. Cell densities (cells/cm²) were approximately the same on both dishes, i.e., 1.2×10^6 cells/55-mm-diameter glass Petri dish (DURAN, Germany) for the 900 MHz GSM experiments and 0.4×10^6 cells/35-mm-diameter Petri dish (NUNC, Denmark) for the 1800 MHz GSM experiments. Furthermore, cell densities were adjusted to obtain similar semi-confluent monolayers after overnight culturing in both dish types. These semi-confluent monolayers of EA.hy926/EA.hy926v1 were exposed to mobile phone radiation. After exposure the cells were harvested either by scraping (I–III) or enzymatically (IV). For the 2DE studies, 10 independent replicates were generated.

The cell cycle analysis was performed for the EA.hy926/EA.hy926v1 cell lines by determining the DNA content of the cells with the standard propidium iodide staining method as described by Leszczynski (Leszczynski 1995). (III)

4.1.2. Primary human umbilical vein endothelial cells

Primary human umbilical vein endothelial cells (HUVEC) were purchased from Lonza, Switzerland, and cultivated according to the manufacturer's instructions. The HUVECs used were a pool of cells from several donors to gain a more heterogeneous sample and thus exclude potential individual variability. For the mobile phone radiation experiments, the cells were removed from the culture flasks by brief trypsinization, washed in cell culture medium and seeded into 35-mm-diameter "CellBind" Petri dishes (Corning, USA). After overnight culturing the medium was replaced with fresh medium and the semi-confluent monolayers of the HUVECs were exposed to mobile phone radiation using an 1800 MHz set-up. After exposure the cells were quickly washed with warm (37 °C) phosphate buffered saline (PBS) and harvested with warm versene (a chelating agent containing EDTA). For the 2DE analysis, 13 independent replicates were generated from the HUVECs.

4.1.3. Primary human brain microvascular endothelial cells

Primary human brain microvascular endothelial cells (HBMEC) were purchased from ScienCell Research Laboratories, USA, and cultivated as per the manufacturer's information. The used HBMECs were from a single donor (only available) and all cells used for the experiments were from the same batch. A vial of cells was cultivated to confluency, after which the cells were de-attached with trypsin and cultivated into 35-mm-diameter "CellBind" Petri dishes (Corning, USA). All the used plates were beforehand coated with 1.5% fibronectin (Sigma, USA). After cultivation for 72 hrs the medium was replaced with new medium and the semi-confluent monolayers of the HBMECs were exposed to 1800 MHz GSM mobile phone radiation. After exposure the cells were quickly washed with warm (37 °C) PBS and harvested with trypsin. For the 2DE analysis, 11 independent replicates were generated from the HBMECs.

4.2. Mobile phone radiation exposures

In all experiments, cell samples were exposed for one hour to mobile phone radiation. The cells were harvested immediately after exposure (without a post-incubation period) to examine the acute response at the protein level.

4.2.1. GSM 900 MHz exposure set-up

Cells were irradiated with simulated mobile phone radiation (900 MHz GSM signal) in a specially constructed exposure system. The system is described in detail by Leszczynski et al. (Leszczynski et al. 2002).

The specially constructed irradiation chamber was placed vertically inside a cell-culture incubator. Two 55-mm-diameter glass Petri dishes were placed inside the chamber in specific locations in such a manner that the E-field vector was parallel to the plane of the culture medium. Temperature-controlled water was circulated through the 9-mm glass-fiber-molded waterbed under the Petri dishes. The RF-EMF signal was generated with the ED Laboratory SG-1240 signal generator and modulated with a pulse duration of 0.577 ms and a repetition rate of 4.615 ms to match the GSM signal modulation scheme. The signal was amplified with an RF Power Labs R720F amplifier and fed to the exposure waveguide via a monopole type feed post. The SAR distribution in the cell culture and the E-field above the cell culture were determined using computer simulations (finite-difference time-domain (FDTD) method). The standard deviation for the SAR distribution inside the Petri dish was 45% based on the computer simulations (Toivo 2011). The simulation results were further validated with measurements.

For all experiments the cells were exposed to GSM mobile phone radiation of 900 MHz for 1 hour at 37 ± 0.3 °C at an average SAR of 2.4 W/kg. In the exposure, for 15% of the cells the SAR was higher than 3 W/kg, and for 0.7% of the cells the SAR was over 5 W/kg based on the non-uniformity of the SAR distribution (Toivo 2011). Sham exposures were generated similarly to the mobile phone radiation exposures but with the signal generator and amplifier turned off.

4.2.2. GSM 1800 MHz exposure set-up

The sXc-1800 exposure system, developed and provided by the IT'IS Foundation (Zurich, Switzerland), was used to expose cells to a GSM signal of 1800 MHz (IV Figure 1, V Figure 1C). A detailed description of the system and dosimetry is presented by Schuderer et al. (Schuderer et al. 2004).

The system consists of two identical exposure chambers mounted inside the same cell culture incubator (NuAire US Autoflow CO₂ Water-Jacketed Incubator, NuAire, USA). One of the chambers acted as a sham control (no radiation) and the other as an experimental chamber (with radiation). The sham exposure chamber and the mobile phone radiation exposure chamber were randomly assigned by the computer program that controlled the exposures. This computer program generated encrypted files with information about the irradiation chamber selection and the environmental monitoring during the experiment. These encrypted files were decoded afterwards by the chamber manufacturer, IT'IS, Zurich, Switzerland, and blinded execution of the experiments was thereby permitted.

The exposure system is fully automated and enables the controlled exposures of cells (H-polarization or at the H-field maximum of the standing wave (Schönborn et al. 2001)) at freely programmable amplitude modulations. Identical environmental conditions existed in both chambers (sham and experimental), since they were both located inside the same cell culture incubator and the inlets of the airflow through them are at the same location. The SAR distribution within the cell culture dish was characterized with a full three-dimensional (3D) electrothermal finite-difference time-domain (FDTD) analysis using the simulation platform SEMCAD (SPEAG, Switzerland). Additionally, the SAR intensity and distribution were verified with measurements using a 1-mm-diameter field probe inserted into the culture medium of the cell culture dish. The non-uniformity of the SAR distribution in the set-up was 23–30% depending on the volume of medium used for the monolayer exposure. In these studies it was estimated to be ca. 28% based on the 3 ml of medium used in cell dishes. (Schuderer et al. 2004)

The simulated mobile phone signal used in the studies was a GSM Talk signal of 1800 MHz. It is characterized by a random change between the discontinuous transmission mode (DTX) and non-DTX or GSM Basic phases. The distribution in time was exponential, with a mean duration of 10.8 seconds for the non-DTX (“talking”) and 5.6 seconds for the DTX (“listening”). The dominant modulation components of this signal were 2, 8, 217, 1733 Hz, and higher harmonics (Tillmann et al. 2007).

The monolayers of human endothelial cells were placed to two 6-dish holders and placed inside the exposure chambers of the set-up in specific locations. In one chamber, randomly selected by the computer program, the cells were exposed to an average SAR of 2.0 W/kg at 37 ± 0.3 °C for 1 hour, while in the other chamber the cells were sham-exposed in similar conditions but without mobile phone radiation. The experiments were performed in a blinded manner and the code was broken at IT'IS afterwards.

4.3. Two-dimensional gel electrophoresis

4.3.1. Sample preparation

The sample preparation methods varied among the different experimental set-ups. The harvested cells were lysed with urea-containing lysing buffer (various contents, for details see publications II–V) for 1 hour at room temperature with occasional vortexing, after which the samples were centrifuged twice for 15 min at 20 000 $\times g$. The protein concentrations were measured using the Bradford method. The amount of total protein used varied from 75 μg (V) up to 250 μg (IV).

4.3.2. Sample labeling

Primary endothelial cell samples (V) were examined using the DIGE technique (Unlü, Morgan & Minden 1997, Alban et al. 2003), whereas the EA.hy926 cell samples were visualized by silver staining (I–IV). The internal standard used for the DIGE experiments was prepared by pooling of the same amount of each sample into one sample. The same amount of total protein from each sample was labeled with Cy fluorescent dyes (GE Healthcare, USA). Each sample was labeled with either Cy3 or Cy5 dye using the “dye swap” principle based on the blinded exposure coding, while the internal standard was always labeled with Cy2 dye. The labeling was performed according to the manufacturer’s instructions. Briefly, 600 pmol of dye per 75 μg of total protein was added to the

sample and labeling was performed for 30 min on ice in darkness. Afterwards, the labeling was quenched with 10 mM free lysine for 10 minutes on ice. A batch of Cy3- and Cy5-labeled samples was pooled with the Cy2-labeled internal standard, and this pool of proteins was separated in a single 2DE.

4.3.3. Isoelectric focusing

Isoelectric focusing was performed using IPGphor apparatus (GE Healthcare) and ready IEF strips (18 cm/pH 3–10 NL or 24 cm/pH 4–7, GE Healthcare). The samples were loaded using an in-gel rehydration in a buffer containing 9 M urea, 2% CHAPS, 0.5% IPG buffer, and 65 mM DTT. The IEF was performed at 20 °C until the desired volt-hours were achieved (65 kVhrs/18 cm, 95 kVhrs/24 cm). For details, see publications II–V.

4.3.4. SDS-PAGE

Before the second-dimension SDS-PAGE, the IEF strips were equilibrated for 15 min with 6 M urea, 30% glycerol, 50 mM Tris-HCl, 2% SDS, and 10 mg/mL dithioereitol (DTT) for 15 min and then for another 15 min in the same buffer, in which 25 mg/mL iodoacetamide (IAA) replaced DTT. In publications I–III, SDS-PAGE was performed using 8% gels similar to Leszczynski et al. (2002). In publications IV & V, 10% gels were used to obtain a better MW separation range. After electrophoresis the gels were processed for protein visualization. For details, see publications II–V.

For molecular weight range determination, MW markers (Bio-Rad, USA) were applied with a paper plug along with SDS-PAGE separation. Separate protein lysates were used (not analytical protein lysates).

4.3.5. Gel staining and image acquisition

Silver-stained gels (I–IV) were first fixed (30% ethanol, 0.5% acetic acid), washed with 20% ethanol and ddH₂O, sensitized with sodium thiosulfate (0.2 g/L), incubated in silver nitrate solution (2 g/L) and developed (potassium anhydride 30 g/L, 37% formaldehyde 0.7 mL/L, sodium thiosulfate 0.01 g/L). The development was stopped with Tris 50 g/L + 0.5% acetic acid, after which the gels were washed twice with ddH₂O and scanned using a GS-710 densitometer (Bio-Rad).

Cy dye-labeled proteins (V) were scanned with a Typhoon Trio scanner (GE Healthcare) with the appropriate excitation and emission wavelengths for Cy2, Cy3, and Cy5 dyes. The PMT voltages were optimized in such a manner

that the maximum signal intensity was approximately on the same level for all of the dyes.

4.3.6. Data analysis

4.3.6.1. PDQuest software

Silver-stained gels (I–IV) were analyzed using PDQuest software (Bio-Rad). In all experiments, 10 replicates from both the mobile phone radiation-exposed and the sham-exposed samples were used. A single gel was selected as a master gel and all the other gels were matched against this master gel. The gels were normalized by the software based the total volume of a gel. The spot volumes of the mobile phone radiation-exposed and sham-exposed sample groups were then compared using statistical testing (t-test, 95% confidence level). The protein spots that visually appeared as technical artifacts (e.g., background areas of silver staining, irregularly shaped dust particles, air bubbles), but were erroneously detected by the software, were manually removed from the analysis.

4.3.6.2. DeCyder software

The datasets containing images from the Cy2, Cy3, and Cy5-labeled samples were acquired with a Typhoon Trio scanner (GE Healthcare) and cropped with ImageQuant software (GE Healthcare) to contain the same pattern of proteins. The datasets were then imported into the DeCyder 6.5 software (GE Healthcare), in which the batch processor was used to detect the spots and match them against a selected master gel. The number of spots was estimated to 10 000 and the volume of 30 000 was used as a cut-off filter. After a brief manual check of the matched spots, the workspace was imported to the DeCyder extended data analysis (EDA) module for statistical analysis. The protein spots found in at least 70% of spot maps were included in the EDA analysis. The Student's t-test (with and without FDR correction) was used to identify differing protein spots. Statistics were performed on log-transformed data, while fold ratios were calculated from standardized abundances. Principal component analysis (PCA) was also performed for the spot maps. The lists containing the statistically significantly differing spots were imported back to the DeCyder biological variation analysis (BVA) module, where the results were evaluated based on the average ratio between the sample groups as well as visually to identify the possible artifacts (e.g., dust or other background artifacts). (V)

4.4. Mass spectrometry

4.4.1. In-gel digestions

Proteins of interest were extracted from several gels and in-gel digested. Before digestion the proteins were reduced with 20 mM DTT in 0.1 M ammonium bicarbonate (NH_4HCO_3) and alkylated with 55 mM IAA in NH_4HCO_3 . The proteins were digested overnight at +37 °C with modified trypsin (sequencing grade modified trypsin, porcine, Promega, USA) in 50 mM NH_4HCO_3 . After overnight digestion, the peptides were extracted with 25 mM NH_4HCO_3 and twice with 5% formic acid. The peptides were concentrated and de-salted using C-18 ZipTips (Millipore, USA) according to the manufacturer's instructions, with the exception of the elution solution being 60% acetonitrile (ACN). (IV)

Additionally, MS identification services were purchased from the Protein Chemistry Laboratory of the Institute of Biotechnology at the University of Helsinki, Finland. (II)

4.4.2. MS data analysis

The tryptic digestions were mixed 1:1 with α -cyano-4-hydroxycinnamic acid matrix and analyzed with the MALDI-TOF-LR-MS (Waters, USA) operating in positive ion reflectron mode. The mass spectra were externally calibrated with an ACTH clip 18-39 (MW 2465.199 Da, Sigma, USA) and internally calibrated with trypsin autolysis peaks (MW 1045.564/2211.108 Da). The peptide mass fingerprints (PMF) for protein identification were searched automatically at the accuracy of 50 ppm from the UniProt database with the ProteinLynx-software (Waters) operating along the instrument. The identifications were also confirmed by a manual search using the Matrix Science Mascot Peptide Mass Fingerprint tool (www.matrixscience.com). (IV)

4.5. Western blotting

The cell samples from the mobile phone radiation exposures were lysed with 2% SDS, 1% protease inhibitor cocktail (Sigma, USA), and the protein concentrations were measured using the Lowry method. The proteins were separated on 1D SDS-PAGE and blotted on a polyvinylidene fluoride (PVDF) membrane, blocked with non-fat dry milk, and exposed to primary antibodies. The respective secondary antibodies containing a horseradish peroxidase (HRP) conjugate (Dako, Denmark) were used. The signal was detected using enhanced

chemiluminescence (ECL). The autoradiography films were scanned with a densitometer and analyzed with Phoretix software (Molecular Probes, USA). For details, see publications II & IV.

4.6. Immunocytochemistry

After the exposure the cell samples were washed with PBS and fixed on glass plates overnight at +4 °C (3.7% paraformaldehyde in fixing buffer: 0.1 M Pipes, 1 mM ethylene glycol tetraacetic acid, 4% polyethyl glycol 8000, 0.1 M NaOH, pH 6.9). After fixing, the cells were permeabilized (0.5% Triton X-100 in fixing buffer for 10 min and 0.1% sodium borohydride in PBS for 10 min) and blocked with 5% bovine serum albumin (BSA). After blocking, the primary antibodies were applied and afterwards the respective fluorescently labeled secondary antibodies. The images were acquired using a Zeiss Axioplan 2 imaging microscope and evaluated by eye. (II)

5. RESULTS

The main results of this study are presented and discussed in publications I–V. A brief summary of the results is presented below.

5.1. Effects on the proteome after 900 MHz GSM exposures (I–III)

EA.hy926 and EA.hy926v1 cells were exposed to a GSM signal of 900 MHz. The exposures were performed during 2001–2004 and the data and the results are presented in publications I–III.

5.1.1. Human endothelial cell line EA.hy926

EA.hy926 cell samples were exposed to GSM mobile phone radiation of 900 MHz for one hour at an average SAR of 2.4 W/kg, and effects on the cell proteome were examined immediately after exposure. Ten independent replicates from the mobile phone radiation and the sham-exposed samples were generated using 2DE with silver staining. In total, 38 protein spots had statistically significantly altered expression levels (t-test, $p \leq 0.05$) between the sample groups (II, Figure 1). The fold ratios between the mobile phone radiation and the sham-exposed samples varied from 0.08 up to 8.9, in addition to a few cases of *de novo* synthesis (fold ratios unpublished). Clear technical artifacts (e.g., from background staining) were removed from the data, but the data still contained some weakly expressed proteins, which were hardly detectable from the background level (III, Figure 2B). (I–III)

A few of the proteins with differing expression levels between the sample groups were identified using mass spectrometry. These included the following (II, Figure 2 and Table 1):

- Vimentin (protein components of class III-intermediate filaments) was found to be expressed in at least two different isoforms differing in molecular weight and isoelectric point. The expression of both isoforms was increased in the samples exposed to mobile phone radiation (2.5-fold, $p = 0.006$, experimental MW/pI ca. 47 kDa/4.4 and 2.2-fold, $p = 0.02$, experimental MW/pI ca. 48 kDa/4.8).
- Isocitrate dehydrogenase 3 (NAD1) was slightly down-regulated in the samples exposed to mobile phone radiation (0.72-fold, $p = 0.03$).
- Heterogeneous ribonucleoprotein H1 was moderately down-regulated in the samples exposed to mobile phone radiation (0.61-fold, $p = 0.03$).

Vimentin expression was further validated using Western blotting and immunocytochemistry (II, Figure 3). Western blotting showed that vimentin was expressed in two forms, and the higher MW form was unaffected after mobile phone radiation exposure. However, the lower MW form was only present in the samples exposed to mobile phone radiation and not in the sham-exposed samples. In addition, a rearrangement of vimentin inside the cells after mobile phone radiation exposure was observed using immunocytochemical staining. Moreover, differences in F-actin and HSP27 expression and cellular localization were observed in immunocytochemical staining (II, Figure 4).

5.1.2. Human endothelial cell line EA.hy926v1

EA.hy926v1, a subclone of the EA.hy926 cell line, was used to examine effects on the proteome level after mobile phone radiation exposure. The cell lines had the same origin, but over the years they have spontaneously begun to exhibit different characteristics. This can be observed, for instance, from their different growth pattern (III, Figure 1).

Similar techniques were used to expose and examine the proteome-level effects in EA.hy926v1 cells to those used in EA.hy926 cells. In total, 45 protein spots had statistically significantly altered expression levels (t-test, $p \leq 0.05$) when comparing the mobile phone radiation and the sham-exposed samples (III, Figure 2C/D). The fold ratios between the sample groups varied from 0.04 up to 6.7 (fold ratios unpublished). In addition, some protein spots appeared with *de novo* synthesis. However, none of these 45 protein spots was the same as those protein spots affected in the EA.hy926 cell samples after exposure. Moreover, the protein expression pattern in the 2DE gels differed between the cell types, and only about a half of the proteins could be matched confidently between the different variants. The time between the two protein separation sets (EA.hy926 and EA.hy926v1) was approximately six months, which might have an influence on the comparability of 2DE protein maps. (III)

5.2. Effects on the proteome after 1800 MHz GSM exposures (IV, V)

EA.hy926 cells and the primary human endothelial cells HUVEC and HBMEC were exposed to a GSM signal of 1800 MHz. The data and the results from these experiments are presented in publications IV & V.

5.2.1. Human endothelial cell line EA.hy926

Cell samples of the EA.hy926 cell line were exposed to GSM mobile phone radiation of 1800 MHz for one hour at an average SAR of 2.0 W/kg, and effects on the proteome of the cells were examined immediately after exposure. Ten independent replicates were generated using 2DE with silver staining. Eight protein spots were found to have statistically significantly altered expression levels (t-test, $p < 0.05$) between the mobile phone radiation and the sham-exposed samples (IV, Figure 2). After exposure to the GSM signal of 900 MHz, 28 proteins spots were found to be altered in the pH range of 4–7 that was used in this study. Out of the eight proteins found here, four of the proteins were down-regulated with fold ratios of 0.33–0.47 and four of the proteins were up-regulated with fold ratios ranging from 1.47 to 2.46. For most of the spots, protein quantities were rather low. (IV)

Out of eight proteins that were affected after mobile phone radiation exposure, three proteins were identified by MS. These proteins were the following (IV, Figure 2 and Table 2):

- Spermidine synthase (SRM) was down-regulated in the samples exposed to mobile phone radiation (0.35-fold, $p = 0.036$).
- A 78 kDa glucose-regulated protein (GRP78) was identified as a fragment of protein. A ca. 55 kDa fragment was up-regulated in the samples exposed to mobile phone radiation (2.46-fold, $p = 0.029$).
- Proteasome subunit alpha type 1 (PSA1) was down-regulated in the samples exposed to mobile phone radiation (0.47-fold, $p = 0.045$).

Identification of the remaining five protein spots with the Maldi-ToF peptide fingerprint (PMF) technique was not successful, and no commercial antibodies were available for SRM or PSA1 proteins. (IV)

The expression of GRP78 protein was further validated using Western blotting. Based on MS identification, it was not possible to identify an exact location for the protein fragment, but a monoclonal antibody (corresponding residues surrounding Gly584, Cell Signaling Technology, USA) identified only a total protein (unpublished data). Using a polyclonal antibody, two forms of the protein representing the whole protein and a fragment were detected in the blot (IV, Figure 4A). However, the expression level of neither of them was altered based on Western blotting. The GRP78 protein amount in 2DE was also rather low and the standard deviation of protein quantity was high. This indicates that the 2DE result is possibly actually a false positive. (IV)

Furthermore, several other proteins were identified on the EA.hy926 2DE gel map to examine the expression of some other interesting proteins. These are listed in publication IV (IV, Figure 3 and Table 1). The 2DE showed no statistically significant differences in vimentin or HSP27 expressions, which

were earlier observed to be altered after exposure to a 900 MHz GSM signal (II, Leszczynski et al. 2002). The Western blots of these proteins also showed no changes in the expression levels of these proteins between the mobile phone radiation and the sham-exposed samples (IV, Figure 4B/C). In addition, based on the MS identifications, the expression levels of HSP60, P-HSP27, and p38 proteins were examined in the 2DE gels, but no statistically significant changes were observed (unpublished data). However, HSP27 phosphorylation/activity was not assessed with a specific phosphorylation assay in this thesis research.

5.2.2. Primary human endothelial cells

The cell samples from the primary human umbilical vein endothelial cells (HUVEC) and the primary human brain microvascular endothelial cells (HBMEC) were exposed to a GSM signal of 1800 MHz for one hour. The proteome of the cell samples was examined using 2DE-DIGE, and 13 independent replicates were produced from the HUVEC and 11 from the HBMEC. In the HUVEC proteome, 35 statistically significantly affected (t-test, $p \leq 0.05$) protein spots were found (V, Figure 3). The maximum average fold ratio between the sample groups was 1.33 for these significantly affected protein spots. In the HBMEC proteome, two statistically significantly affected (t-test, $p \leq 0.05$) protein spots with average fold ratios of -1.16 and +1.1 were observed when comparing the sample groups (V, Figure 4). However, when the false discovery rate (FDR) correction ($p \leq 0.05$) was applied to the statistical tests, all statistically significantly affected spots were recognized as false positives. All the spots found to be differentially expressed before the FDR correction were also manually checked. The average fold ratios of protein spots between the sample groups were close to 1.0 and the spots with the highest average fold ratios were visually recognized as technical artifacts (e.g., dust particles based on the extremely sharp peak geometry). In addition, principal component analysis (PCA) of the spot maps demonstrated differences between the cell types, but not between the exposure conditions (V, Figure 5). (V)

The differences between the cell types were also examined in the same analysis. In total, 368 protein spots were found to differ between the cell types (t-test, $p \leq 0.0001$, with FDR correction). Out of these 368 protein spots, 145 spots were differentially expressed between the cell types by more than 2-fold up or down (V, Figure 2). A few of these proteins were also identified with MS and, for example, tropomyosin showed a 5.8-fold decrease in HUVEC in comparison to HBMEC. The different expression levels were clearly observed in all samples, irrespective of the exposure conditions (unpublished data).

6. DISCUSSION

6.1. Effects on the proteome after mobile phone radiation exposure

In this thesis research, the effects on the proteome of four different types of human endothelial cells were examined after short-term exposure to mobile phone radiation. In general, proteomics was found to be an effective tool to screen the expression of several hundreds of proteins simultaneously, and applicable in mobile phone radiation research. It was observed that the cell type as well as exposure conditions have an impact on the responses at the proteome level following mobile phone radiation exposure. Changes in the proteome of the human endothelial cell line EA.hy926 were detected after exposure to a 900 MHz GSM signal, and changes in vimentin expression were further confirmed with other methods. A few other proteins were also identified, but their expression levels were not further validated. The proteome of the EA.hy926v1 cell line was also affected after 900 MHz GSM exposure, but differently from the EA.hy926 cells, although both cell lines have the same origin. Furthermore, a few changes were observed in the proteome of EA.hy926 cells after 1800 MHz GSM exposure. However, the number of affected proteins was lower in comparison to the 900 MHz GSM studies, and none of the affected proteins was the same in the two studies. Alteration of the GRP78 expression level was observed in 2DE, but it could not be confirmed with other techniques. This underlines the importance of data validation. The proteome of the primary human endothelial cells did not show any changes after exposure to an 1800 MHz GSM signal.

The presented results show that more changes were observed on the proteome level after exposure to 900 MHz GSM than to 1800 MHz GSM. There are a few possible explanations for this:

- i) The different exposure frequencies (900 vs. 1800 MHz). However, there is currently no known mechanism by which a particular frequency could cause these observed differences, while another frequency does not cause similar effects. However, this issue of different frequencies should be further investigated. If possible, the same exposure set-up could be applied with different frequencies to address this issue.
- ii) The differences in SAR distribution in the cell culture dishes of the exposure set-ups. Certain differences in SAR distributions were evident; however, these differences were minor and, for instance, only 0.7% of cells gained a higher SAR than 5 W/kg in the 900 MHz GSM set-up (Toivo 2011). Thus, it is unlikely that these differences would be observed using proteomics techniques. Furthermore, the EA.hy926 cells were exposed to a

1800 MHz GSM signal at an SAR of 5 W/kg for one hour, and the Western blot did not reveal any changes in the expression level of HSP27, vimentin or p38MAPK (unpublished data), similarly to the earlier 900 MHz GSM exposures (II, Leszczynski et al. 2002). Therefore, it is unlikely that the different SAR distributions in the used set-ups would alone explain the observed differences in the responses after the exposures.

- iii) The more reliable 2DE technology in the later studies (silver staining vs. DIGE, data analysis). 2DE technology has improved over time. The primary cells were examined using 2DE-DIGE, which is a more reliable technique than silver staining used in the earlier studies. The improved reliability was observed as a decrease in variation and in the number of observed false positives. Additionally, in the EA.hy926 1800 MHz GSM study, the fold ratios were examined more carefully before assigning the affected proteins. In the earlier studies only statistics were used, and as some of the fold ratios were close to 1.0, the proteins could not be considered actually affected. Therefore, methodological variation is likely to partly explain the observed differences (see further discussion in chapter 6.2).
- iv) Potential differences in the cells used. It is also possible that some spontaneous modifications have occurred in the EA.hy926 cell line used, and it might have become less responsive over the time. These spontaneous modifications are known to occur in cell lines if they are over-subcultured (for review, see e.g., Hughes et al. 2007). This may be likely, as the EA.hy926 cells originally had an abnormal chromosomal number around 80 (Edgell, McDonald & Graham 1983) and were based on HUVEC cells, which often exhibit an aneuploidic or polyploidic nature (e.g., Nichols et al. 1987, Wagner et al. 2001, Kimura et al. 2004). The possibility of such modifications in the EA.hy926 cell line is supported by the presence of the EA.hy926v1 cell line, which is a variant of the same cell line but shows different growth characteristics and thus indicates the potential genetic instability of this cell line. The potential genetic modifications are also supported by the recent Western blots, in which no alterations were observed in the expression of vimentin or p38MAPK in the EA.hy926 cells after exposure to a 900 MHz GSM signal (unpublished data), similarly to the earlier studies (II, Leszczynski et al. 2002).

To address the variation in all these results, the EA.hy926 cells should be examined simultaneously using modern proteomics techniques, both exposure set-ups, and different passages of the cell line, as it seems that the EA.hy926 cell line is a potential responder to mobile phone radiation exposure, unlike the primary cells.

The most convincing evidence of cellular-level effects is shown by the vimentin expression level, which was affected after 900 MHz GSM mobile phone radiation exposure, as especially observed from the Western blots. However, this effect was not observed after the 1800 MHz GSM exposure. Other research groups have not examined vimentin expression after mobile phone radiation exposure, but some changes have been observed in other proteins relating to cellular structures, e.g., connexins and gap junction like-structures (Cervellati et al. 2009). Using immunocytochemistry, the expression of vimentin and cellular localization of HSP27 were found to be affected after the 900 MHz GSM exposure. However, the results of the immunocytochemical staining were only evaluated by eye and are not therefore completely reliable. Leszczynski et al. and Yu et al. also reported changes in HSP27 expression after mobile phone radiation exposure (Leszczynski et al. 2002, Yu et al. 2008). However, the exposure assessment by Yu et al. was not reported, and their results cannot therefore be considered conclusive. Meanwhile, several other studies have reported no changes in the HSP27 expression level (e.g., Lee et al. 2006, Vanderwaal et al. 2006, Hirose et al. 2007). In this thesis research, no changes were observed in HSP27 expression after 1800 MHz GSM exposure. There have also been other studies suggesting that the cellular responses might depend on the cell type and/or exposure. For example, Sanchez et al. observed a decrease in HSC70 expression in human dermal fibroblasts after 900 MHz GSM exposure (Sanchez et al. 2006), whereas after 1800 MHz GSM exposure no effects were observed in these cells (Sanchez et al. 2007). The different responses on the mRNA level depending on the cell type and exposure conditions also support the observation that the responses after the mobile phone radiation exposure depend on cell type and exposure conditions (III, Remondini et al. 2006).

To date, only a few proteomics studies *in vitro* related to mobile phone radiation research have been published. Zeng et al. concluded that no changes were observed after mobile phone radiation exposure (Zeng et al. 2006). Their observation is similar to the ones made in this thesis research using human primary endothelial cells, although more modern and reliable techniques were applied here. Kim et al. used the same cells as Zeng et al. and found certain proteins, GRP78, PIN1, and glucosidase II, to be affected in single gels, but the results were not reproducible with any other techniques (Kim et al. 2010). Li et al. reported four proteins to be affected, two hnRNP K, HSP70, and one unidentified protein, but the results were not confirmed with other techniques. Further validation would give more impact to this study, as 2DE was only performed in triplicate using silver staining (Li et al. 2007). So far, the highest number of affected and identified proteins after mobile phone radiation exposure

has been detected by Gerner et al. (Gerner et al. 2010). They reported 14 affected proteins spots, e.g., HSP-family proteins, T-complex proteins, annexins, and BIP, i.e., GRP78. Gerner et al. used an approach that differed from all the other studies, as they used ^{35}S -labeling and actually measured the protein synthesis. Differences were observed in protein synthesis, while the fluorescently labeled gels showed no differences in total protein expression. This would suggest that mobile phone radiation has a greater effect on protein synthesis than on the actual total expression of proteins, indicating an imbalance in the protein level due to the exposure (Gerner et al. 2010). However, the reliability of this study was also limited, because only triplicate gels were used and the observations were not confirmed with any other techniques.

Similarly to the research presented in this thesis, Kim et al. and Gerner et al. also observed changes in GRP78 protein expression. However, validation of the expression of this protein in this study and by Kim et al. revealed no changes. Thus, the finding of effects on GRP78 might more likely represent a limitation of the 2DE technique, since it has been shown that several proteins are repeatedly reported to be affected in different kinds of proteomics studies (Petrak et al. 2008). These proteins include, e.g., HSP27, enolase 1, peroxiredoxins, vimentin, annexins, HSC71, keratins, GRP78, and RHOGDI. For instance, HSP27 was identified in 31%, vimentin in 19% and GRP78 in 13% of the studies published during a three-year period in the journal *Proteomics* (Petrak et al. 2008). Extreme caution was suggested in the interpretation of differential expression of the most frequently identified proteins, as these might represent more the lack of depth in 2DE analysis (experimental design) than real differences due to biological condition examined. The expression of these proteins should at least be confirmed with other methods before assigning them as affected, as was done in this study and in that by Kim et al.

In summary, in the studies presented in this thesis, proteome responses after mobile phone radiation exposure seem to vary depending on the cell type and exposure. Although some minor effects exist, they are not necessarily global effects. This is in line with the observations of mobile phone radiation research in general, as most of the observed effects have so far been contradictory. Therefore, at this point it is not possible to identify any unique cellular-level response caused by mobile phone radiation. Neither is it possible to identify a likely mechanism or potential physiological or pathological effects on the cellular level due to mobile phone radiation exposure. Furthermore, it is not possible to predict the presence or absence of any potential health effect due to mobile phone radiation exposure.

6.2. General remarks on proteomics results in the light of technological development

Proteomics data need to be evaluated in light of technological development. Proteomics technologies have been widely available for about two decades, and several methodological improvements have been introduced during this time. The most important of these are probably the development of staining methods and improvements in data analysis.

In the earlier studies presented in this thesis, silver staining was used to visualize proteins, as it was still regularly used at that time. However, only fluorescent dyes are nowadays used for quantitative proteomics. Among the silver-stained protein analyses, there were protein spots that were very faint and spots for which changes in the expression level were less than 2-fold, which were assigned as affected only by statistical analysis. Moreover, the normality of data was not investigated when the statistical analysis was performed. These analyses were directly based on raw data, and not on log-transformed data, which might have caused bias in the results. Furthermore, false discovery rate correction was not applied in the data analysis, and in fact, the false positive rate was not exceeded in any of the studies. Therefore, some of the observations of affected proteins might actually have been false positives. Thus, based on current knowledge, effects on the cellular proteome in EA.hy926 and EA.hy926v1 cells after mobile phone radiation exposure might not be as significant as originally presented. However, despite the limitations of the methodology, the effects on vimentin protein expression were also observed with other methods. Conversely, no effects were proven for GRP78 protein expression in Western blot analysis after 1800 MHz GSM exposure. This indicates that GRP78 is possibly a false positive detection in 2DE, which is supported by the low protein quantity and high standard deviation in 2DE quantification (IV). This underlines the importance of data validation using other methods, especially when 2DE is not performed using state-of-the-art technology. The last study, using 2DE-DIGE technology and the latest requirements in data analysis methodology (e.g., log transformation of data and false discovery rate correction), showed no effects on the proteome of two human primary cell lines. Due to the technology used in this study, the results are very significant in showing no immediate effects on the proteome of primary human endothelial cells immediately after exposure to an 1800 MHz GSM signal. Meanwhile, the strength of the 2DE-DIGE system was demonstrated by the observed differences between the cell types.

The main strength of the studies presented in this thesis is the number of replicates collected for the proteomics analyses. All the proteome studies were based on at least 10 biological replicates, which is unprecedented in the field of mobile phone radiation research. All remaining published proteome studies *in*

vitro in this research field, although only a few exist, are based on triplicate gels and other staining techniques than DIGE. In the DIGE system, three replicates are enough to show 2-fold differences if the biological variation is small (e.g., in cell lines) and the technical variation due to the system is reduced (Karp et al. 2007). In systems other than DIGE, the gel-to-gel variation is much higher and more replicates are needed to observe such differences.

6.3. Future aspects

The results presented here demonstrate that the proteome response after mobile phone radiation exposure depends on the cells used as well as on the exposure conditions. The proteome of EA.hy926 cells was affected after exposure to 900 MHz GSM mobile phone radiation, whereas the changes in the proteome after 1800 MHz GSM exposure were much weaker. The observed differences in EA.hy926 responses should be addressed with modern techniques to determine their causes. A study comparing the effects between the exposure set-ups using state-of-the-art proteomics techniques is currently in progress. The preliminary results of this study indicate that the responses after mobile phone radiation exposures are not similar to those observed earlier (unpublished data). However, this study has not taken into account the potential spontaneous genetic changes in the cell line, which should also be examined.

Furthermore, these experiments only focused on a single exposure condition, i.e., exposure for one hour at an SAR average close to 2 W/kg, and the proteome responses were only examined immediately after exposure. The time and dose selection was based on a previous study published by Leszczynski et al., as several changes were reported in that study (Leszczynski et al. 2002). However, other researchers (e.g., Gerner et al. 2010) have suggested that longer exposure times are needed to observe responses on the proteome level. Additionally, it might be worthwhile to allow a post-incubation time after the exposures to enable potential changes to appear on the translational level. Recent Western blot data on heat shock exposures (43 °C, 1 hour) of EA.hy926 cells have demonstrated that HSP70 protein expression levels are increased a few hours after the treatment, but not immediately after (unpublished data). However, some studies have suggested that even with a post-incubation time, responses following mobile phone radiation exposure might not be observed (e.g., Chauhan et al. 2006a, 2006b, Kim et al. 2010). Furthermore, chronic exposures with occasional sampling could reveal a response to long-lasting exposures without the need for time point selection. Additionally, cell selection for further studies is important, as it seems that responses depend on the cell type and even on the stage of the cells. For example, Gerner et al. found that metabolically

inactive mononuclear cells were less affected than active mononuclear cells after mobile phone radiation exposure (Gerner et al. 2010). The use of several cell types would also reveal potentially responding cells.

Regarding the proteomics studies, cellular and technical fractionation would be useful to gain further depth in 2DE analysis. With these improvements, the decreased number of typical responders (Petrak et al. 2008) in 2DE studies would be observed. Furthermore, other techniques should also be used in protein expression studies, as the basic shot-gun proteomics techniques do not provide information on, for instance, the protein half-lives or localization (if total cell lysates are used). Additionally, it might be worthwhile to examine the potential effects after mobile phone radiation exposure at the individual cell level, as the more crude proteomics techniques require rather large and comprehensive effects in a total cell population before they are observed. For instance, Newman et al. have introduced in yeast the use of single-cell proteomics, which allows quantitative single-cell measurements of proteins (Newman et al. 2006). However, this technique is currently available only for certain model organisms, although it might be applicable in the future.

7. CONCLUSIONS

In this thesis, the results of proteomics analysis of human endothelial cells after short-term mobile phone radiation exposure are presented. Proteomics was found to be an effective and applicable tool to examine responses at the proteome level after mobile phone radiation exposure, although so far it has not been extensively applied in this research field. Proteomics techniques allow the large-scale screening of several hundreds, even thousands, of proteins simultaneously, and are thus more efficient than single endpoint techniques, especially if an appropriate experimental design is applied. However, proteomics requires rather large and comprehensive effects in total cell populations before they are observed, i.e., effects at the individual cell level cannot be detected with the proteomics techniques used.

In this study, several changes were observed in the proteome of the human endothelial cell line EA.hy926 after the exposure to 900 MHz GSM mobile phone radiation. In addition, the proteome of a variant of the same cell line, EA.hy926v1, was affected after the same exposure, but different proteins were altered compared to EA.hy926 cells. However, changes in the proteome of EA.hy926 cells were weaker after exposure to an 1800 MHz GSM signal than after the 900 MHz GSM exposure. The proteome of primary cells was not affected after 1800 MHz GSM exposure when examined using 2DE-DIGE technology. The earlier studies using EA.hy926 cells were partly limited due to certain technological aspects of 2DE (staining, data analysis), but the extensive replication as well the validation of some of the protein endpoints with other methods are strengths of this study. Due to the technology used here, the last study using primary cells and 2DE-DIGE technology is very significant in showing no immediate effects on the proteome of primary human endothelial cells after 1800 MHz GSM exposure.

The results presented in this thesis regarding the proteome-level effects after mobile phone radiation exposure are contradictory. The results for EA.hy926 cells suggest that minor effects occur, whereas no effects were observed using the more advanced 2DE-DIGE technology and primary cells. The responses with EA.hy926 cells varied according to the cell type and exposure conditions, and the consistent responses at the cellular level could not therefore be identified. Further research is recommended to understand the variation in responses and whether consistent cellular-level responses exist.

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APPENDIX 1

Table 3. Studies on heat shock proteins after mobile phone radiation exposure.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies in vivo				
Fritze et al. 1997	Rats (Wistar), brains	890–915 MHz GSM, 900 MHz CW 0.3 / 0.17 W/kg (GSM), 1.5 / 0.84 W/kg (GSM), 7.5 / 4.2 W/kg (CW) 4 hrs sampling immediately and 24 hrs after exposure	Hsp70, gene expression (mRNA <i>in situ</i> hybridization), protein expression (immunohistochemistry)	Increase in <i>Hsp70</i> mRNA after 7.5 W/kg CW exposure, transient in 24 hrs No effects on protein expression
De Pomerai et al. 2000	<i>C. Elegans</i> (PC72, PC161)	750 MHz CW 0.001 W/kg 18 hrs sampling after exposure	<i>Hsp16</i> , reporter gene activity (β-galactosidase activity, GFP fluorescence)	Activation of <i>Hsp16</i> gene Publication retracted later
Weisbrot et al. 2003	<i>Drosophila melanogaster</i> (Oregon R)	900/1900 MHz GSM commercial mobile phone ~ 1.4 W/kg (not measured) 1 hrs/day, 10 days sampling after exposure	HSP70, protein expression (Western blotting)	Increase in HSP70 protein expression level Inadequate dosimetry
Lee J.S. et al. 2005	Mice (<i>Hsp70.1</i> -deficient), major tissues	849 MHz, 1763 MHz CDMA 0.4 W/kg (whole body) 2x45min/day, 5 days/week, 10 weeks sampling 4, 8, and 10 weeks	HSP25, HSP70, HSP90, protein expression (Western blotting)	No effects
Dawe et al. 2006	<i>C. Elegans</i> (PC72, PC161)	1000 MHz CW 4–40 mW/kg 2.5, 20 hrs sampling at 2- or 4-hr intervals during exposure and after exposure	<i>Hsp16</i> , reporter gene activity (MUG assay, GFP fluorescence)	No non-thermal effects

Table 3. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies <i>in vivo</i>				
Sanchez et al. 2008	Rats (10-week-old hairless female), skin	900 MHz, 1800 MHz GSM 2.5, 5 W/kg 2 hrs (5 W/kg) sampling immediately afterwards 2 hrs/day, 5 days/week, 12 weeks (2.5, 5 W/kg) sampling 72 hrs after the last exposure	HSP25, HSP70, HSC70, protein expression (immunohistochemistry)	No effects (Effects on positive control)
Dawe et al. 2008	<i>C. Elegans</i> (PC72)	1800 MHz GSM, CW 1.8 W/kg 2.5 hrs sampling after exposure	<i>Hsp16</i> , reporter gene activity (MUG assay)	No effects Minor effect observed if background levels otherwise elevated
Finnie et al. 2009	Female pregnant mice (BALB/c), descendant brains	900 MHz PW (GSM type) 4 W/kg (whole body) 60 min/day, from day 1 to day 19 of gestation sampling immediately prior to parturition (day 19)	HSP25, HSP32, HSP70, protein expression (immunohistochemistry)	No effects on HSP expression in mice brains (No induction of HSP32 or HSP70 at all, the HSP25 expression similar in all mice brains)
Watilliaux et al. 2010	Developing rats (Wistar) (post-natal days 5, 15, or 35), brains	1800 MHz GSM 1.7–2.5 W/kg 2 hrs sampling 24 hrs after exposure	HSP60, HSC70, HSP70, HSP90, protein expression (Western blotting)	No effects (No effects either on several glial markers, e.g., GFAP)

Table 3. Continued.

Reference	Study material	Frequency, modulation SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies <i>in vitro</i>				
Leszczynski et al. 2002	Human endothelial cell line EA.hy926	900 MHz GSM 2.4 W/kg 1 hr sampling 1, 2, 6, and 8 hrs after the start of exposure (HSP27) sampling 1, 2, and 5 hrs after the start of exposure (P-HSP27)	HSP27, protein expression (Western blotting), P-HSP27, protein phosphorylation (³² P-labeling)	Increase in HSP27 phosphorylation and expression, transient in a few hours after the end of the exposure
Capri et al. 2004	Human mononuclear cells PBMC	1800 MHz GSM intermittent (10 min on/ 20 min off) (Basic, DTX, Talk modulations) 2.0 W/kg (Basic, Talk), 1.4 W/kg (DTX) 44 hrs sampling after exposure	HSP70, protein expression (flow cytometry)	No effects
Czyz et al. 2004	Mouse embryonic stem (ES) cells: Pluripotent R1 ES cells, wild type (wt) D3, and p53-deficient ES cells	1710 MHz GSM (217 Hz, Talk modulation) 1.5, 2.0 W/kg 6, 48 hrs sampling immediately after 6-hr exposure sampling after 48-hr exposure during cultivation (0, 2, 5 days) and differentiation (2, 5, 7, 10, 15 days)	Hsp70, gene expression (RT-PCR)	Increase in <i>Hsp70</i> mRNA level throughout differentiation period in the p53-deficient ES cells after the GSM 217 Hz modulated signal, no effects on other cells or after the GSM Talk signal exposure
Caraglia et al. 2005	Human oropharyngeal epidermoid carcinoma cancer cell line KB	1950 MHz (modulation not specified) 3.6 W/kg 1, 2, 3 hrs sampling after exposure	HSP27, HSP70, HSP90, protein expression (Western blotting)	Increase in HSP27 expression (maximum 3.5-fold at 1 hr time point) Increase in HSP70 expression (maximum at 2 hrs time point) Decrease in HSP90 expression (5-fold at 3 hrs)

Table 3. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies in vitro				
Lim et al. 2005	Human peripheral blood (monocytes, lymphocytes)	900 MHz GSM, CW 0.4, 2.0, 3.6 W/kg 20 min, 1, 4 hrs sampling after exposure	HSP27, HSP70, protein expression (flow cytometry)	No effects (Effects on positive control)
Lixia et al. 2006	Human lens epithelial cells hLEC	1800 MHz GSM 1, 2, 3 W/kg 2 hrs sampling after exposure	HSP70, gene expression (RT-PCR), protein expression (Western blotting)	Increase in HSP70 protein expression after 2 and 3 W/kg exposures, no effects on mRNA levels
Sanchez et al. 2006	Human normal primary epidermal keratinocytes NHEK, Human normal primary dermal fibroblasts NHDF, Human reconstructed epidermis	900 MHz GSM 2 W/kg 48 hrs sampling after exposure	HSP27, HSP70, HSC70, protein expression (immunohistochemistry)	Decrease in HSC70 expression in fibroblasts Increase in HSP70 expression in the reconstructed epidermis, if cultivated 3 or 5 weeks (Effects on positive control)
Vanderwaal et al. 2006	Human epithelial carcinoma cell line HeLa S3, Human endothelial cell line EA.hy926	847 MHz TDMA, 1900 MHz GSM 5 W/kg (TDMA), 3.7 W/kg (GSM) 1, 2, 24 hrs (TDMA), 1, 2, 5 hrs (GSM) sampling after exposure	HSP27, protein expression and phosphorylation (Western blotting)	No effects (Effects on positive control)
Lee JS. et al. 2006	Human T-lymphocyte Jurkat cells, Rat primary astrocytes	1763 MHz CDMA 2, 20 W/kg 30 min, 1 hr sampling 6, 12, 24 hrs after exposure	HSP27, HSP70, HSP90, protein expression (Western blotting)	No effects (Effects on positive control)

Table 3. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies <i>in vitro</i>				
Simko et al. 2006	Human monocyte cell line Mono Mac 6	1800 MHz CW, GSM (217 Hz, non-DTX modulation) 2 W/kg 1 hr sampling 2 hrs after exposure	HSP70, protein expression (Western blotting, flow cytometry)	No effects (Effects on positive control)
Lantow et al. 2006a	Human umbilical cord blood-derived primary monocytes	1800 MHz GSM (DTX modulation) 2 W/kg 1 hr sampling 0, 1, 2 hrs after exposure	HSP70, protein expression (flow cytometry)	No effects (Effects on positive control)
Lantow et al. 2006b	Human monocyte cell line Mono Mac 6, Human myelogenous leukemia cell line K562	1800 MHz GSM (DTX modulation) 2.0 W/kg 1 hr sampling 0, 1, 2 hrs after exposure	HSP70, protein expression (flow cytometry)	No effects (Effects on positive control)
Chauhan et al. 2006a	Human lymphoblastoma cells TK6	1900 MHz PW intermittent (5 min on, 10 min off) 1, 10 W/kg 6 hrs sampling immediately and 18 hrs post-exposure	<i>HSP27, HSP70B</i> , gene expression (RT-PCR)	No effects (Effects on positive control)
Chauhan et al. 2006b	Human promyelocytic leukemia cell line HL-60, Human monocyte cell line Mono Mac 6	1900 MHz PW intermittent (5 min on, 10 min off) 1, 10 W/kg 6 hrs sampling immediately and 18 hrs post-exposure	<i>HSP27, HSP70B</i> , gene expression (RT-PCR)	No effects (Effects on positive control)

Table 3. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies <i>in vitro</i>				
Chauhan et al. 2007b	Human glioblastoma cell line U87MG	1900 MHz PW 0, 1, 10 W/kg 24 hrs sampling after exposure	<i>HSP27, HSP40, HSP70B, HSP71, HSP90AA1, HSP105</i> , gene expression (RT-PCR)	No effects (Effects on positive control)
Sanchez et al. 2007	Human normal primary epidermal keratinocytes NHEK, Human primary dermal fibroblasts NHDF	1800 MHz GSM (217 Hz modulation) 2 W/kg 48 hrs sampling after exposure	<i>HSP27, HSC70, HSP70</i> , protein expression (immunohistochemistry)	No effects (Effects on positive control)
Hirose et al. 2007	Human glioblastoma cell line A172, Human fibroblast cell line IMR-90	2142.5 MHz WCDMA, CW 80, 250, 800 mW/kg (A172, WCDMA) 80 mW/kg (A172, CW) 2, 24, 48 hrs (A172) 80, 800 mW/kg (IMR-90, WCDMA) 80 mW/kg (IMR-90, CW) 2, 28 hrs (IMR-90) sampling after exposure	<i>HSP27, P-HSP27</i> , protein expression and phosphorylation (bead-based multiplex assay) <i>HSP27, HSP70</i> , protein expression and cellular localization (immunocytochemistry) <i>HSP27, HSP40, HSP70, HSP105/110</i> , gene expression DNA chip analysis	No effects on <i>HSP27</i> (Effects on positive control) No effects on the cellular location of <i>HSP27, HSP70</i> No effects on gene expression (Effects on positive control)
Huang et al. 2008b	Mouse auditory hair cells HEI-OC1	1763 MHz CDMA 20 W/kg 6, 12, 24 hrs sampling after exposure	<i>HSP27, HSP70, HSP90</i> , protein expression (Western blotting)	No effects

Table 3. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies <i>in vitro</i>				
Valbonesi et al. 2008	Human trophoblast cell line HTR-8/SVneo	1800 MHz GSM (217 Hz modulation) 2 W/kg 1 hr sampling 0, 1, 3 hrs after exposure	HSC70, HSP70, protein expression (Western blotting) HSC70, HSP70A, HSP70B, HSP70C, gene expression (RT-PCR)	No effects (Effects on positive control)
Franzellitti et al. 2008	Human trophoblast cell line HTR-8/ SVneo	1800 MHz CW, GSM (217 Hz, Talk modulation) 2 W/kg 4, 16, 24 hrs sampling after exposure	HSP70, HSC70, protein expression (Western blotting) HSC70, HSP70A, HSP70B, HSP70C, gene expression (RT-PCR)	Altered <i>HSP70C</i> mRNA transcript levels after certain exposure types (up after 24 hrs exposure to the GSM 217 Hz signal, down after 4 and 16 hours exposure to the GSM Talk signal) No effects on protein expression or gene expression of other HSP70 family members (Effects on positive control)
Yu et al. 2008	Human lens epithelial cells hLEC	1800 MHz RF-EMF 1, 2, 3, 4 W/kg 2 hrs sampling after exposure	HSP27, HSP70, HSP90, protein expression (Western blotting)	Increase in HSP27 and HSP70 expression in all conditions, no effects on HSP90 Exposure assessment reported insufficiently

Table 4. Studies on proto-oncogenes after mobile phone radiation exposure.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies <i>in vivo</i>				
Fritze et al. 1997	Rats (Wistar), brains	890–915 MHz GSM, 900 MHz CW 0.3 / 0.17 W/kg (GSM), 1.5 / 0.84 W/kg (GSM), 7.5 / 4.2 W/kg (CW) 4 hrs sampling immediately and 24 hrs after exposure	<i>C-Fos</i> , <i>C-Jun</i> , gene expression (mRNA <i>in situ</i> hybridization) <i>C-FOS</i> , <i>FOS B</i> , <i>C-JUN</i> , <i>JUN</i> <i>B</i> , <i>JUN D</i> , protein expression (immunohistochemistry)	No effects No effects either on the proliferation or on the expression of specific astroglial and microglial marker proteins (Effects due to immobilization)
Finnie et al. 2005	Mice (C57BL/6NTac), brains	900 MHz PW (GSM type) 4 W/kg (whole body) 1 hr sampling after exposure	<i>C-FOS</i> , protein expression (immunohistochemistry)	No effects after exposure (Effects due to immobilization)
Finnie et al. 2006b	Female pregnant mice (BALB/c), descendant brains	900 MHz PW (GSM type) 4 W/kg (whole body) 60 min/day, from day 1 to day 19 of gestation sampling immediately prior to parturition (day 19)	<i>C-FOS</i> , protein expression (immunohistochemistry)	No effects
Lopez-Martin et al. 2006	Rats (male Sprague–Dawley), picrotoxin treatment, brains	900 MHz GSM untreated: 0.42 W/kg (brain), 0.24 W/kg (mean) treated: 0.27 W/kg (brain), 0.15 W/kg (mean) 2 hrs sampling 1 hr after exposure	<i>C-FOS</i> , protein expression (immunohistochemistry)	Increase in <i>C-FOS</i> expression in the presence of picrotoxin, no effects without pre-treatment

Table 4. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies <i>in vivo</i>				
Finnie et al. 2007	Mice (C57BL/6N/Tac), brains	900 MHz PW (GSM type) 4 W/kg (whole body) 60 min/day, 5 days/week, 104 weeks sampling after exposure	C-FOS, protein expression (immunohistochemistry)	No effects
Yilmaz et al. 2008	Rats (Sprague–Dawley), brains and testes	900 MHz GSM, commercial mobile phone 0.52 W/kg (whole body) 20 min/day, 1 month sampling after exposure	BCL-2, protein expression (immunohistochemistry)	No effects on rat brain or testes
Lopez-Martin et al. 2009	Rats (male Sprague–Dawley), picrotoxin treatment, brains	900 MHz GSM untreated: 0.05 W/kg (brain), 0.05 W/kg (mean) treated: 0.03 W/kg (brain), 0.03 W/kg (mean) 2 hrs sampling 1 hr after exposure	C-FOS, protein expression (immunohistochemistry)	Increase in C-FOS expression in the presence of picrotoxin
Studies <i>in vitro</i>				
Ivaschuk et al. 1997	Rat pheochromocytoma cells PC12	836.55 MHz TDMA average densities of 0.09, 0.9, and 9 mW/cm ² , for 0.9 mW/cm ² SAR 2.6 mW/kg 20, 40, 60 min intermittent (20 min on/ 20 min off) total incubation times 20, 60, 100 min sampling after exposure	<i>C-Fos</i> , <i>C-Jun</i> , gene expression (Northern blotting)	Decrease in <i>C-Jun</i> transcript levels after 20-min exposure to 9 mW/cm ² , no other effects

Table 4. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies in vitro				
Goswami et al. 1999	Mouse embryo fibroblasts C3H 10T 1/2 (exponential growth phase and serum-deprived cells)	835.62 MHz CW, 847.74 MHz CDMA 0.6 W/kg 4 days continuous exposure sampling 24 hrs, 4 days	<i>Jun</i> , <i>Fos</i> , <i>Myc</i> , gene expression (RT-PCR)	Increase in <i>Fos</i> mRNA levels in exponential growth phase cells in transit to the plateau phase and in plateau-phase cells, effects larger in the CW-exposed samples than in the CDMA-exposed samples
Czyz et al. 2004	Mouse embryonic stem (ES) cells: Pluripotent R1 ES cells, wild type (wt) D3, and <i>p53</i> -deficient ES cells	1710 MHz GSM (217 Hz, Talk modulation) 1.5, 2.0 W/kg 6, 48 hrs sampling immediately after 6-hr exposure sampling after 48-hr exposure during cultivation (0, 2, 5 days) and differentiation (2, 5, 7, 10, 15 days)	<i>Bcl-2</i> , <i>C-Jun</i> , <i>C-Myc</i> , gene expression (RT-PCR)	Transient up-regulation of <i>C-Jun</i> and <i>C-Myc</i> mRNA levels in early stages (day 2, 5, and 5+2 of EB differentiation) with the GSM 217 Hz signal in the <i>p53</i> -deficient cells, no effects on other cells or after the GSM Talk signal exposure
Whitehead et al. 2005	Mouse embryo fibroblasts C3H 10T 1/2 (exponential growth phase, transition to plateau phase)	847.74 MHz CDMA, 835.62 MHz FDMA, 836.55 MHz TDMA 5.2, 10 W /kg 4 days continuous exposure sampling 24 hrs, 4 days	<i>C-Fos</i> , gene expression (RT-PCR)	No effects (Effects on positive control)
Merola et al. 2006	Human neuroblastoma cell line LAN-5	900 MHz GSM 1.0 W/kg 48 and 72 hrs sampling after exposure	B-MYB, N-MYC, protein expression (Western blotting)	No effects

Table 4. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies in vitro				
Chauhan et al. 2006a	Human lymphoblastoma cells TK6	1900 MHz PW intermittent (5 min on, 10 min off) 1, 10 W/kg 6 hrs sampling immediately and 18 hrs post-exposure	<i>JUN</i> , <i>FOS</i> , <i>MYC</i> , gene expression (RT-PCR)	No effects (Effects on positive control)
Chauhan et al. 2006b	Human promyelocytic leukemia cell line HL-60, Human monocyte cell line Mono Mac 6	1900 MHz PW intermittent (5 min on, 10 min off) 1, 10 W/kg 6 hrs sampling immediately and 18 hrs post-exposure	<i>C-MYC</i> , <i>C-FOS</i> , <i>C-JUN</i> , gene expression (RT-PCR)	No effects (Effects on positive control)
Buttiglione et al. 2007	Human neuroblastoma cells SH-SY5Y	900 MHz GSM 1 W/kg 5, 15, 30 min, or 6, 24 hrs sampling after exposure	<i>BCL-2</i> , survivin, <i>BAK</i> , <i>BAX</i> , gene expression (RT-PCR)	Decrease in <i>BCL-2</i> and survivin after 24 hrs exposure (<i>BCL-2</i> also 6 hrs after), in parallel with an impaired cell cycle progression No effects on <i>BAK</i> , <i>BAX</i>
Del Vecchio et al. 2009	Rat primary cortical neurons	900 MHz GSM 1 W/kg 5 days continuous exposure sampling 24 hrs	<i>C-Jun</i> , <i>C-Fos</i> , gene expression (RT-PCR)	No effects

Table 5. Studies on signal transduction pathway and certain structural proteins after mobile phone radiation exposure.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies in vivo				
Weishrot et al. 2003	<i>Drosophila melanogaster</i> (Oregon R)	900/1900 MHz GSM commercial mobile phone ~ 1.4 W/kg (not measured) 1 hrs/day for 10 days sampling after exposure	ELK-1, protein phosphorylation (Western blotting)	Increase in ELK-1 phosphorylation
Lee JS. et al. 2005	Mice (<i>Hsp70.1</i> -deficient), major tissues	849 MHz, 1763 MHz CDMA 0.4 W/kg (whole body) 2x45min /day, 5 days/week, 10 weeks sampling 4, 8, and 10 weeks	ERK1/2, P-ERK, JNK1/2, P-JNK, p38MAPK, P-p38MAPK, protein expression and phosphorylation (Western blotting)	No effects on the expression or phosphorylation of ERK, JNK, p38MAPK
Dasdag et al. 2009	Rats (male Wistar albino), brains	900 MHz GSM 0.17–0.58 W/kg 2 hours/day, 7 days/week, 10 months sampling after exposure	p53, protein expression (immunohistochemistry, semi-quantitative scoring system)	No effects on p53 (Decrease in apoptosis)
Yan et al. 2009	Rats (Sprague-Dawley), brains	800 MHz AMPS, 1900 MHz Personal communication services mode (PCS), commercial mobile phone 1.8 W/kg AMPS, 1.18 W/kg PCS 6 hours/day, 7 days/week, 18 weeks sampling after exposure	Calcium ATP-ase, Endothelin, Neural Cell Adhesion Molecule, Neural Growth Factor, gene expression (RT-PCR)	Mild increase in the mRNA levels of all examined genes (Some insufficiency in the exposure assessment)
Ammari et al. 2010	Rats (Sprague-Dawley), brains	900 MHz GSM 1.5 W/kg (brain average), 45 min/day 6 W/kg (brain average), 15 min/day 5 days/week, 8 weeks sampling 3, 10 days after exposure	GFAP, protein expression (immunohistochemistry)	Increase in GFAP expression

Table 5. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies <i>in vivo</i>				
Watiliaux et al. 2010	Developing rats (Wistar) (post-natal days 5, 15, or 35), brains	1800 MHz GSM 1.7 – 2.5 W/kg 2 hrs sampling 24 hrs after exposure	GFAP, GLAST, GLT1, serine racemase, protein expression (Western blotting)	No effects
Studies <i>in vitro</i>				
Leszczynski et al. 2002	Human endothelial cell line EA.hy926	900 MHz GSM 2.4 W/kg 1 hr sampling 1, 2, 6, and 8 hrs after the start of exposure	p38MAPK, protein expression (Western blotting)	Increase in p38MAPK expression, transient in a few hours after the end of the exposure
Czyz et al. 2004	Mouse embryonic stem (ES) cells: Pluripotent R1 ES cells, wild type (wt) D3, and p53-deficient ES cells	1710 MHz GSM (217 Hz, Talk modulation) 1.5, 2.0 W/kg 6, 48 hrs sampling immediately after 6-hr exposure sampling after 48-hr exposure during cultivation (0, 2, 5 days) and differentiation (2, 5, 7, 10, 15 days)	p21, <i>Erg-1</i> , gene expression (RT-PCR)	Transient up-regulation of the p21 mRNA level in the early stages (day 2, 5, and 5+2 of EB differentiation) with the GSM 217 Hz signal in the p53-deficient cells, no effects on other cells or after GSM Talk signal exposure
Caraglia et al. 2005	Human oropharyngeal epidermoid carcinoma cancer cell line KB	1950 MHz (modulation not specified) 3.6 W/kg 1, 2, 3 hrs sampling after exposure	RAS, RAS activity, RAF1, ERK1/2, AKT, PGSK3, P3K, p38K, P-p38K, JNK1, P-JNK1, protein expression and activity (Western blotting, gel kinase assay)	Decrease in the expression and the activity of RAS Decrease in RAF1 expression Decrease in ERK1/2 activity (no changes in expression) Decrease in AKT expression (no changes in activity) Increase in P3K expression Decrease in p38 activity (no changes in expression) Increase in JNK1 activity (no changes in expression)

Table 5. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies in vitro				
Nikolova et al. 2005	Mouse embryonic stem (ES) cells	1710 MHz GSM (217 Hz modulation) intermittent (5 min on/30 min off) 1.5 W/kg 6, 48 hrs sampling 7, 11, 17, and 23 days after plating	<i>Bcl-2</i> , <i>Bax</i> , <i>Gadd45</i> , <i>p53</i> , <i>Nurr1</i> , <i>TH</i> , Nestin, gene expression (RT-PCR)	Increase in <i>Bax</i> mRNA levels at day 17, increase in <i>Gadd45</i> mRNA levels at day 23, decrease in <i>Nurr1</i> mRNA levels at day 7, no changes in cell physiology
Lee JS. et al. 2006	Human T-lymphocyte Jurkat cells, Rat primary astrocytes	1763 MHz CDMA 2, 20 W/kg 30 min, 1 hr sampling 6, 12, 24 hrs after exposure	ERK, P-ERK, JNK, P-JNK, p38, P-p38, protein expression and phosphorylation (Western blotting)	No effects (Effects on positive control)
Hirose et al. 2006	Human glioblastoma cell line A172, Human fibroblast cell line IMR-90	2142.5 MHz WCDMA, CW 80, 250, 800 mW/kg (A172, WCDMA) 80 mW/kg (A172, CW) 24, 48 hrs (A172) 80 mW/kg (IMR-90, WCDMA, CW) 28 hrs (IMR-90) sampling after exposure	p53, protein expression and phosphorylation (bead-based multiplex assay) <i>TP53</i> , <i>TP53BP2</i> , <i>APAF1</i> , <i>CASP9</i> , gene expression (RT-PCR)	No effects (Effects on positive control)
Friedman et al. 2007	Human epithelial carcinoma cell line HeLa, Fischer rat fibroblast 3T3-like cell line Rat1	800, 875, 950 MHz RF-EMF 0.07 mW/cm ² / 5, 10, 20, 30 min (ERK) 0.1, 0.2, 0.31 mW/cm ² / 10 min (P-ERK) 0.23 mW/cm ² / 5, 10, 20, 30 min (JNK, p38) 0.005, 0.03, 0.11 mW/cm ² / 5, 10, 20, 30 min (ERK) 0.17 mW/cm ² / 2, 12 min + incubation 5, 10 min (ERK) sampling after exposure unless otherwise stated	ERK, P-ERK, JNK, P-JNK, p38, P-p38, protein expression and phosphorylation (Western blotting)	Activation of the ERK1/2 pathway (rapid response in various exposure conditions) No effects on JNK, p38 No SAR estimates

Table 5. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Frequency, modulation Exposure time Sampling time	Endpoints	Results (& comments)
Studies <i>in vitro</i>				
Burtigione et al. 2007	Human neuroblastoma cells SH-SY5Y	900 MHz GSM 1 W/kg 5, 15, 30 min, or 6, 24 hrs sampling after exposure	<i>ERG-1</i> , <i>p53</i> gene expression (RT-PCR) P-ERK1/2, P-JNK, P-ELK-1, protein phosphorylation (Western blotting)	Increase in <i>ERG-1</i> mRNA levels after 5 min exposure, transient in 6 hrs No effects on <i>p53</i> Phosphorylation of ERK1/2, JNK, ELK-1, transient in 6 hrs
Huang et al. 2008b	Mouse auditory hair cells HEI-OC1	1763 MHz CDMA 20 W/kg 15, 30, 60, 120 min sampling after exposure	ERK, P-ERK, JNK, P-JNK, p38, P-p38, protein expression and phosphorylation (Western blotting)	No effects (Effects on positive control)
Yu et al. 2008	Human lens epithelial cells hLEC	1800 MHz RF-EMF 1, 2, 3, 4 W/kg 5, 15, 30, 60, 120 min sampling after exposure	ERK1, P-ERK1, ERK2, P-ERK2, JNK1, P-JNK1, JNK2, P-JNK2, p38, P-p38, protein expression and phosphorylation (Western blotting)	ERK1/2 activated after 5 min exposure, peaked at 30 min, lasted 2 hrs JNK1/2 phosphorylated after 2 hrs exposure (highest after 2 W/kg exposure) No effects on p38 Exposure assessment not reported
Cervellati et al. 2009	Human trophoblast cell line HTR-8/SVneo	1817 MHz GSM (217 Hz modulation) 2 W/kg 1 hr sampling after exposure	<i>Cx32</i> , <i>Cx37</i> , <i>Cx40</i> , <i>Cx43</i> , <i>Cx45</i> , gene expression (RT-PCR) Cx40, Cx43, protein expression and localization (Western blotting, immunocytochemistry)	Increase in <i>Cx40</i> and the <i>Cx43</i> mRNA levels, no changes in the protein expression level or the protein delocalization Decrease in intercellular gap junction-like structures

Table 5. Continued.

Reference	Study material	SAR (local/whole body, if applicable) Exposure time Sampling time	Endpoints	Results (& comments)
Studies in vitro				
Del Vecchio et al. 2009	Rat primary cortical neurons	900 MHz GSM 1 W/kg 5 days continuous exposure sampling 1, 3, 5 days	Beta-thymosin, gene expression (RT-PCR)	Increase in beta-thymosin mRNA levels at 4 th cellular division, a corresponding decrease in the number of neurites
Hirose et al. 2010	Rat primary microglial cells	1950 MHz WCDMA 0.2, 0.8, 2.0 W/kg 2 hrs sampling 24, 72 hrs after the exposure	TNF- α , IL-1 β , IL-6, protein expression (antibody bead kit)	No effects
Lee KY et al. 2011	Human breast cancer MCF7 cells	837 MHz CDMA, 1950 MHz WCDMA (single exposure or combination of signals) 4 W/kg (single), 2*2 W/kg (combination) 1 hr sampling 0, 2, 10, 24, 48 hrs after exposure	p53, p21, cyclin A, cyclin B1, cyclin D1, CDK2, CDK4, protein expression (Western blotting)	No effects (Effects on positive control)

Table 6. Transcriptomics studies after mobile phone radiation exposure.

Reference	Study material	Frequency, modulation Time points (exposure/sampling)*	Experimental platform, # of replicates	Results (& comments)
Studies in vivo				
Belyaev et al. 2006	Rats (Fischer 344), cerebellum	915 GSM 0.4 W/kg whole body 2 hrs	Affymetrix U34 GeneChips containing 8800 rat genes n=3	<ul style="list-style-type: none"> 12 genes affected, fold ratios 1.34–2.74, diverse functions No further validation
Paparin et al. 2008	Mice (Balb/cJ), brains	1800 MHz GSM 1.1 W/kg whole body, 0.2 W/kg whole brain 1 hr	Affymetrix MOE 430A arrays containing over 22000 probes, n=3, pooled RNA	<ul style="list-style-type: none"> More stringent data analysis showed no changes Less stringent conditions showed 75 genes affected (1.5–2.8 up or 0.67–0.29 down), the expression of 30 potentially affected genes validated using RT-PCR, none of them showed alterations The authors concluded that there is no consistent indication of a gene expression modulation
Studies in vitro				
Pacini et al. 2002	Normal human skin fibroblasts Detroit 550	902.4 MHz, GSM commercial mobile phone 0.6 W/kg 1 hr	Atlas Human Array Trial Kit, 82 genes, n=1	<ul style="list-style-type: none"> 14 genes differentially expressed (mitogenic signal transduction genes, cell growth inhibitors, apoptosis) No further validation, n=1, commercial mobile phone
Lee S. et al. 2005	Human promyelocytic leukemia cell line HL-60	2450 MHz PW 10 W/kg 2, 6 hrs	Serial Analysis of Gene Expression (SAGE), n=1	<ul style="list-style-type: none"> 2 hrs: 221 genes affected 6 hrs: 759 genes affected No further validation, n=1

*Sampling immediately after exposure unless otherwise stated

Table 6. Continued.

Reference	Study material	Frequency, modulation Time points (exposure/sampling)*	Experimental platform, # of replicates	Results (& comments)
Studies <i>in vitro</i>				
Whitehead et al. 2006a, 2006b	Non-osteogenic mouse pluripotent cell line C3H 10T1/2	835.6 MHz FDMA 847.7 MHz CDMA 5 W/kg 24 hrs	Affymetrix U74Av2 GeneChips containing ca. 9200 unique genes, n=3	<ul style="list-style-type: none"> The number of probes with an expression change > 1.3-fold was less than or equal to the expected number of false positives Positive control No further validation on the potential target genes as all were rejected based on false positive rate calculations
Qutob et al. 2006	Human glioblastoma-derived cell line U87MG	1900 MHz PW 0.1, 1.0, 10.0 W/kg 4 hrs	Agilent human 22K microarray slides (Human 1A), over 18000 human genes, n=5	<ul style="list-style-type: none"> No effects after exposure Positive control 6 <i>HSP</i> genes confirmed with RT-PCR, no effects In the data analysis a gene appearance in all the five replicates was required
Hirose et al. 2006	Human glioblastoma cells A172 Human fibroblasts IMR-90	2142.5 MHz WCDMA, CW A172: 80, 250, 800 mW/kg (WCDMA), 80 mW/kg (CW) A172: 24, 48 hrs IMR-90: 80 mW/kg (WCDMA&CW) IMR-90: 28 hrs	Affymetrix Human genome HG-U133 Plus2.0 microarrays, ca. 33000 human genes, n=2	<ul style="list-style-type: none"> No consistent effects in two experiments Positive control The expression of four p53-related genes confirmed with RT-PCR

* Sampling immediately after exposure unless otherwise stated

Table 6. Continued.

Reference	Study material	Frequency, modulation Time points (exposure/sampling)*	Experimental platform, # of replicates	Results (& comments)
Studies <i>in vitro</i>				
Remondini et al. 2006	Human neuroblastoma cells NB69, Human endothelial cell line EA.hy926, Human quiescent T-lymphocytes, Human monocytes U937, Human microglial cells CHME5, Human hematopoietic leukemia cells HL-60	NB69: 1800 MHz GSM intermittent (5 min on/10 min off), 2 W/kg, 24 hrs EA.hy926: 900 MHz GSM, 2.4 W/kg, 1hr 1800 MHz GSM, 2 W/kg, 1 hr T-lymphocytes: 1800 MHz GSM intermittent (10 min on/20 min off), 1.4 W/kg, 44 hrs U937: 900 MHz GSM, 2 W/kg, 1 hr CHME5: 900 MHz GSM, 2 W/kg, 1 hr HL-60: 1800 MHz GSM intermittent (5 min on/5 min off), 1.0 W/kg, 24 hrs 1800 MHz GSM, 1.3 W/kg, 24 hrs	Human Unigene RZPD-2 cDNA array containing about 75000 cDNA clones, RNA pooled from several exposures, n=1 for hybridizations	<ul style="list-style-type: none"> EA.hy926: effects after the 900 MHz exposure (32 clones), no effects after the 1800 MHz exposure U937: effects (34 clones) HL-60: effects after the intermittent exposure (12 clones), no effects after the continuous exposure although SAR higher No effects on other cells No consistent signature after exposure No validation of results, n=1 for hybridizations
Zeng et al. 2006	Human breast cancer cell line MCF-7	1800 MHz GSM intermittent (5 min on/10 min off) 2, 3.5 W/kg 24 hrs	Affymetrix GeneChip Test3 containing 14500 genes, n=2	<ul style="list-style-type: none"> Five responding genes (PPP1R12A, TBL1X, EFNB2, TOP1, MTDH) RT-PCR did not confirm these, thus, the authors concluded no effects were actually observed n=2

*Sampling immediately after exposure unless otherwise stated

Table 6. Continued.

Reference	Study material	Frequency, modulation Time points (exposure/sampling)*	Experimental platform, # of replicates	Results (& comments)
Studies <i>in vitro</i>				
Gurisk et al. 2006	Human neuroblastoma cell line SK-N-SH	900 MHz PW (GSM 217 Hz modulation) 0.2 W/kg 2 hrs (sampling 2 hrs post-exposure)	Affymetrix Human Focus Gene arrays including ca. 8400 genes, n=1	<ul style="list-style-type: none"> • Six genes slightly down-expressed (LIM, Nap1L1, CCPG1, ACADM, BMAL1, Rbbp4) • RT-PCR did not validate two of these genes (CCPG1 and BMAL1) and, thus, the authors concluded that no effects were observed • n=1
Hirose et al. 2007	Human glioblastoma cells A172, Human fibroblasts IMR-90	2142.5 MHz WCDMA, CW 80 and 800 mW/kg (WCDMA) 80 mW/kg (CW) A172: 2, 24, 48 hrs IMR-90: 2, 28 hrs	Affymetrix Human genome HG-U133 Plus2.0 microarrays, ca. 33000 human genes, n=2	<ul style="list-style-type: none"> • No effects • Positive control • n=2
Chauhan et al. 2007b	Human glioblastoma-cell line U87MG, Human monocyte cell line Mono Mac 6 (MM6)	1900 MHz PW intermittent (5 min on/10 min off) for MM6 0.1, 1.0, 10.0 W/kg (0.1 W/kg U87MG only) 6 hrs (MM6), 24 hrs (U87MG) sampling also 18 hrs post-exposure for MM6	Agilent human 22K microarray slides (Human 1Av2), over 18000 human genes, n=5	<ul style="list-style-type: none"> • No effects after exposure • Positive control • 6 <i>HSP</i> genes confirmed with RT-PCR for the U87MG cells, no effects • In the data analysis a gene appearance in all the five replicates was required
Zhao TY et al. 2007	Primary mouse neurons and astrocytes	1900 MHz GSM, commercial mobile phone, on and stand by -modes SAR unknown 2 hrs	GEArray Q series mouse apoptosis array, containing 96 genes, n=2	<ul style="list-style-type: none"> • Up-regulation of caspase-2, caspase-6 and <i>Asc</i> in both cell types, also <i>Bax</i> up-regulated in astrocytes • RT-PCR confirmed results • Exposure assessment inadequate, n=2

* Sampling immediately after exposure unless otherwise stated

Table 6. Continued.

Reference	Study material	Frequency, modulation Time points (exposure/sampling)*	Experimental platform, # of replicates	Results (& comments)
Studies <i>in vitro</i>				
Zhao R et al. 2007	Primary rat neurons	1800 MHz GSM intermittent (5 min on/ 10 min off) 2 W/kg 24 hrs	Affymetrix Rat Neurobiology U24 array, containing over 1200 transcripts n=1	<ul style="list-style-type: none"> 34 affected genes (fold ratios 1.15–1.62) Most of the changes further validated with RT-PCR n=1 for array, n=3 RT-PCR
Huang et al. 2008a	Human T lymphoma cell line Jurkat T	1763 MHz CDMA 10 W/kg 24 hrs	Applied Biosystems 1700 full genome expression array, 30000 genes n=5	<ul style="list-style-type: none"> 10 genes affected 1.3–1.8–fold, among them two cytokine receptors No further validation for the gene expression, the authors concluded no effects on global gene expression were observed
Huang et al. 2008b	Mouse auditory hair cells HEI-OC1	1763 MHz CDMA 20 W/kg 24 hrs sampling 5 hrs after the exposure	Applied Biosystems 1700 full genome expression array, 32000 genes n=3	<ul style="list-style-type: none"> 29 genes affected (18 annotated genes and 11 ESTs) more than 1.5-fold No consistent groups of functional categories No further validation, the authors concluded that as the number of affected genes is low those genes might be actually false positives No effects either on cell cycle, DNA damage, or stress response
Sekijima et al. 2010	Human glioblastoma cell line A172, Human neuroglioma H4, Human fibroblasts IMR-90	2142.5 MHz WCDMA and CW 80, 250, 800 mW/kg 96 hrs	Affymetrix Human Genome Array, ca. 16000 to 19000 genes, n=2	<ul style="list-style-type: none"> Minor effect ($p < 0.05$, max fold ratio 1.14) on A172 and H4 cells, no effect on IMR-90 cells Positive control No further validation The authors concluded no effects were observed No effects on either cell growth or viability

*Sampling immediately after exposure unless otherwise stated

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